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Wheat for the Nontraditional Warm Areas

D.A. Saunders, technical editor

UNDP/CIMMYT

Wheat for the Nontraditional Warm Areas

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D.A. Saunders, technical editor

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On the Cover: Near the Burmese-Thai border, Weera Suriwong (left), of northern Thailand's Fang District Agricultural Extension Office, inspects the dryland crop of a first-time wheat grower (Photo by Gene Hettel).

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Acknowledgments

"Increasing Wheat Production in Warmer and Stresssed Environments" is a substantial project—one of the few global endeavors of the United Nations Development Programme (UNDP). UNDP can be proud of its sponsorship of this conference—Wheat for the Nontraditional, Warm Areas—and the support it provided to many of the participants so that they could travel great distances to come to Brazil.

In addition to UNDP, we would like to acknowledge other donors who supported various speakers at this conference including the German Agency for Technical Cooperation (GTZ) and the International Fertilizer Development Center (IFDC).

We recognize the tremendous efforts of the Brazilian groups in putting on this conference—the Brazilian Enterprise for Agricultural Research (EMBRAPA) for its assistance in planning this conference; the Organization of Paraná State Cooperatives (OCEPAR) and the Agronomic Institute of Paraná (IAPAR) for their sponsorship of the Wednesday field trip; and to the scientists who translated the paper and poster abstracts into Portuguese (available in a separate booklet): Carlos Riede, Y.R. Mehta, Dionisio Brunetta, Augusto Baier, Erlei Melo Reis, and Chr. Diederichs.

We are very grateful for the assistance we received from the Consul General and the First Secretary of the Brazilian Embassy in Asunción in processing visas for the numerous participants coming from around the world. We also acknowledge the help of Paraguayan government officials for facilitating border crossings between Brazil and Paraguay.

We want to thank the paper and poster presenters for getting their material in well ahead of the meeting dates. This means the proceedings will be published quickly because much of the technical and style editing was done during the conference by Dr. David Saunders and Gene Hettel, respectively, to whom we give our special thanks.

We thank Ms. Liciane Duda Bonatto, who designed the conference logo used on all of the correspondence and other conference materials. We thank our tireless support staff—the secretaries, Mrs. Anna Maria Chavez and Mrs. Silvana Bianchi and Mr. Erico Orelar and the rest of the CIMMYT Asunción office staff for all their hard work.

We thank our overworked translators, Ms. Patricia Fischer and Ms. Genevieve Pelisson, who did a spectacular job of simultaneous translation from English to Spanish and vice versa.

It was at least 2 years ago that Mohan Kohli, Pat Wall, and Girma Bekele in the CIMMYT/Asunción office began contemplating this conference. As time went by, planning and preparation took more and more of their time in organizing what turned out to be a very successful conference—something they can be very proud of. They deserve a very special thanks.

Preface

The International Conference on Wheat for the Nontraditional, Warm Areas was held at Foz do Iguaçu, Brazil, July 29-August 3, 1990. This was the third conference sponsored by the United Nations Development Programme (UNDP) and the International Maize and Wheat Improvement Center (CIMMYT) designed to discuss constraints and research developments for wheat production in warmer areas of the world. In these warm areas, until quite recently, wheat had not been contemplated as a commercial crop. One hundred and twenty-nine delegates from 28 countries attended the conference.

The first stage of the UNDP/CIMMYT project, during which the first conference (Wheats for More Tropical Environments) in this series was held in September 1984 in Mexico, concentrated more on germplasm development—especially germplasm with resistance to aggressive diseases of the warmer areas. As suitable germplasm started to become available, the importance of crop management increased, as shown during the second conference (Wheat Production Constraints in Tropical Environments) held in January 1987 in Thailand; this led to increased emphasis on crop management during the second phase of the project.

This conference, which comes at the beginning of the project's third phase—Increasing Wheat Production in Warmer and Stresssed Environments—involved 31 papers and 17 poster displays presented in these proceedings. They describe the wealth of research being conducted in the nontraditional areas and highlight the multi-disciplinary nature of the problems now being addressed, particularly with reference to sustainability of cropping systems. The need for multi-disciplinary research was stressed at the first two conferences and the progress is now obvious.

Panel discussions investigated present and future strategies on the key issues of sustainability, breeding and disease research, plant nutrition, and the value of international networking for cost-effective problem solving. The section of these proceedings beginning on page 447 summarizes the highlights of these stimulating discussions.

We hope that the forum this conference provided leads to closer working ties among scientists, networks, and national and international agricultural research centers. These proceedings will serve as a valuable reference source (along with the proceedings of the first two conferences published by UNDP and CIMMYT) for future work on wheat for the more marginal areas of the world.

D.A. Saunders
Technical Editor

M.M. Kohli
P.C. Wall
Conference Organizers

Welcome from Brazilian Officials

Marcos Vieira, Executive President, Agronomic Institute of the State of Paraná (IAPAR)

It is a great honor and pleasure to welcome you to the state of Paraná. We are grateful to CIMMYT for selecting Paraná as the site for this Conference on Wheat for the Nontraditional, Warmer Areas. We firmly believe that this meeting will bring us up to date on technology that will help increase wheat production not only in Paraná but all of Brazil.

Paraná is probably one of the best examples of how research can contribute toward a real increase in the productivity of a crop—in this case wheat. Approximately 1 decade ago, the average wheat yield in the state hovered around 1 t/ha. Although we still do not have stable production and the wheat crop depends a lot on climatic conditions in a given year, the average wheat yield today is 2.2 t/ha. Basically, this has happened due to the results of research, extension work, and technical assistance in the field.

Specifically, three technological advances have played important roles in this production increase:

- More varieties adapted primarily to the constraints of low fertility, acid soils, and the presence of toxic levels of aluminum.
- Better disease and insect control.
- Improved crop management techniques including conservation practices.

We are sure that, during this international symposium, the exchange of new information will be of great use to all of us. Once again, we are very delighted to host this conference of distinguished scientists and wish all of you a very productive week.

Ivo Marcos Carraro, Technical Director, Organization of Paraná State Cooperatives (OCEPAR)

As a representative of the farmer cooperatives and in the name of all the wheat producers of the state of Paraná, I would like to welcome all of the participants. I want to thank the conference organizers for selecting our state as the location for this important event.

As Dr. Vieira has already mentioned, the state of Paraná can certainly be cited as a region where very spectacular advances in wheat production have occurred. However, even with the dramatic production increases, the 1980s were times of extreme difficulties for our farmers due to increased prices for inputs and constant price reductions for their crops. Even so, Paraná's wheat farmers have been able to overcome these serious difficulties thanks mainly to their dynamic interactions with the research and extension sectors and credit organizations.

Farmers represented by OCEPAR created their own research program in 1974 devoted to such disciplines as breeding, soil management, general agronomy, and seed production. OCEPAR has also maintained harmonious relationships with public sector research institutes such as IAPAR and the Brazilian Agricultural Research Enterprise (EMBRAPA) and international institutions such as

CIMMYT. In 1990, approximately 52% of the wheat area in Paraná was planted to varieties developed by the OCEPAR research program.

To a large extent, the work done by OCEPAR is paid for by member farmers through a small tax on their production, which is earmarked for OCEPAR's research fund. We consider this support from farmers to be extremely important in maintaining critical links between the research and production sectors.

In conclusion, we hope that your experiences during the coming week will serve to improve the quality of research so vitally needed to increase food production for a hungry world.

Luiz Ricardo Pereira, Director, National Wheat Research Center (CNPT), Brazilian Agricultural Research Enterprise (EMBRAPA)

On behalf of the President of EMBRAPA, Dr. Murilo Xavier Flores, and myself, I wish to convey our greetings to you all. For those of you who are visiting us for the first time, I might explain that EMBRAPA has the mandate to coordinate and execute research in agriculture and animal husbandry on a national level. Together with other institutions, both state and private, we form the Agropecuarian Cooperative Research System (ACRS).

It is important to mention that, especially in the case of wheat research, an excellent relationship has been developed among different institutions that work with this cereal. Thanks to this cooperative effort, as mentioned by Ing. Carraro, much has been achieved in terms of the integration of wheat research in Brazil.

In the decade of the 1970s, the average on-farm yield of wheat in Brazil was around 0.9 t/ha. During the last 5 years, this yield has doubled to approximately 1.8t/ha. Presently, farmers who adopt the recommended technologies are obtaining yields in excess of 3 t/ha—sometimes as high as 5 t/ha. At the experiment station level, yields of 6 t/ha (rainfed) and 8 t/ha (irrigated) have been obtained.

In 1979, Brazilian farmers planted 4.1 million hectares of wheat that produced 2.8 million tons of grain. In 1989, the cultivated wheat area was 300,000 ha less, but production was 2.5 million tons more (5.3 million tons).

In recent years, several new technologies have been offered to farmers through the excellent exchange of information that exists among the various Brazilian and international institutions.

We must highlight the germplasm and information exchange with CIMMYT. CNPT was involved with CIMMYT in the early 1970s, even before the creation of EMBRAPA. At that time, CIMMYT collaborated with the Ministry of Agriculture, which was then responsible for agricultural research. With the creation of EMBRAPA in 1974, the collaboration with CIMMYT was further strengthened to develop new germplasm with high yield potential.

We are very happy to have so many distinguished visitors here to discuss the important issue of growing wheat in the nontraditional, warm environments. Thank you for coming.

KEYNOTE ADDRESS

Trends of Wheat Production in the Warmer Areas: Major Issues and Economic Considerations

R.A. Fischer, Director, Wheat Program, and D.R. Byerlee, Director, Economics Program, CIMMYT, Mexico

Abstract

This paper examines recent biological and economic developments as they relate to the economic rationale for pursuing greater wheat production in nontraditional, warm areas. On the biological front, good progress is reported on the development of better resistance to major diseases, but genetic resistance to the key abiotic stresses involved, namely heat and drought, has not been so clearly identified. However, improved crop management has led to unexpectedly high yields (>5 t/ha) in some hot dry, irrigated locations, giving cause for optimism. Economic issues discussed include slowing production growth in traditional wheat producing countries, current GATT (General Agreement on Tariffs and Trade) negotiations on export subsidies, slowing of consumption growth in tropical countries in the 1980s due to policy changes driven by economic reform, but continuing dependence on imports (>60%), a large significant part of which is food aid in sub-Saharan Africa and tropical Latin America.

The economics of growing wheat in warmer areas is discussed. Best prospects exist where wheat helps intensify cropping systems without incurring a heavy opportunity cost in foreign exchange and where production is not capital intensive. Given the expected progress on the biological front, we anticipate continuing gains in wheat production in nontraditional, warm areas over the next decade under more reasonable economic scenarios resulting from fewer policy distortions both in world markets and at the national level.

Introduction

One may make much fun of the juxtaposition of a biologist and an economist as co-authors of this opening address: problem solver versus gloom sayer, or perhaps merely a sign of the times. Although an awkward duet, we are put together on this program because of the paramount importance of considering the economic issues involved in the effort to increase wheat production in the nontraditional, warm areas. In fact, the CIMMYT project dedicated to this objective—and recently granted funding from the United Nations Development Programme (UNDP) for an additional 3 years—is one of the activities of CIMMYT most challenged by donors.

The criticism is that wheat for warmer areas (i.e., trying to make a temperate crop perform in a tropical environment) inevitably makes no sense biologically or economically. While use of the term "tropical" has been a point of confusion for some throughout the duration of this project, the criticism has some validity and cannot be dismissed lightly. It can be pointed out that soybeans were successfully introduced to North America and Brazil and maize to Europe, so the separation of traditional and nontraditional niches seems flawed. Besides, wheat has already moved into nontraditional, warm areas over the last decade or so. Still, introduction of a crop into nontraditional areas takes time and resources, and recent wheat production in

these areas may have been artificially supported. We must be sure that wheat production in these areas continues to make economic sense for the nations involved.

The economic considerations cannot, however, be separated from the biological ones—expected yields, expected input requirements, expected externalities, and expected yields of alternative crops are all part of the economic equation. Economists can work too readily with assumptions; they need biologists, breeders, and agronomists to keep them on track—and of course vice versa. Therefore, in this paper, we will look at the recent aspects of production and consumption of wheat in warmer areas and at new issues in the biology of wheat for these areas, before passing to a consideration of the economic sense of such an endeavor.

Definition of Warmer Environments

The climatic characteristics of the warmer areas need no detailed explanation here because they have been discussed thoroughly in two preceding conferences (Klatt 1985, Fischer 1985, Saunders 1988, Tanner 1988, Wall 1988). Dr. A.R. Klatt stated during the 1984 conference in Mexico: "CIMMYT is interested in successful wheat production in warmer (more tropical) areas of the world where it is generally not a traditional crop." He added that "these tropical wheat environments include most of the areas lying between the Tropics of Cancer (23°N) and Capricorn (23°S) plus adjacent areas with tropical or subtropical climates" (Klatt 1985). These areas can be divided on the basis of mean temperature of the coolest month: above 22.5°C as very hot, 17.5-22.5°C as hot, and below 17.5°C as warm or warm temperate. The "warm" category was introduced to include important areas of intermediate altitudes (500-1500 masl) where wheat is being grown within the tropics, sometimes in the summer season (e.g., parts of East Africa, Peru, and central Brazil), and the lower altitude areas adjacent to the tropics (e.g., southeastern Paraguay, the Chaco of Argentina, southern Brazil, and northern Bangladesh).

This classification based on mean temperature is helpful, but obviously simplistic because it ignores the other months in which the crop grows and especially the rate of temperature rise after the coolest month that can range from 1 to 5°C per month. The classification also ignores the possible importance of the diurnal temperature range that can be as little as 5°C or as much as 20°C.

All authors have pointed to the usefulness of distinguishing between the humid and dry warmer areas. Fischer (1985) defined humid locations as those with an average estimated leaf-to-air day time vapor pressure deficit (VPD) of less than 10 mb. These places often have dew formation in the early morning and are usually subject to cloud cover and sometimes rain—all factors that favor foliar and head diseases. On the other hand, dry locations (mean daily VPD > 10 mb) usually have negligible disease pressure, and, due to the virtual absence of clouds, more solar radiation. High VPD may have other consequences that will be discussed later.

Fischer (1985) has further suggested that the yield potential of wheat with an adequate water supply in these warmer environments is best indicated by the photothermal quotient (i.e., solar radiation divided by the mean temperature—or mean temperature minus a base temperature). On this basis with all other factors being equal, yield potentials in the hot dry environments are usually 30% or more higher than those in the hot humid ones.

Figures 1, 2, and 3 attempt to show the approximate boundaries of hot and very hot regions according to our definition. Although VPD is not shown, sunshine hours as a percentage of the maximum possible are given. Humid areas tend to be those with less than about 80% of maximum possible sunshine.

The above discussion defines two of the dozen or so mega-environments recognized by the CIMMYT Wheat Program (See Fischer and Varughese 1989 for a discussion on the mega-environment classifications), namely hot humid (ME5A) and hot dry (ME5B); both assume a good water supply to the crop. As pointed out earlier, our interest also

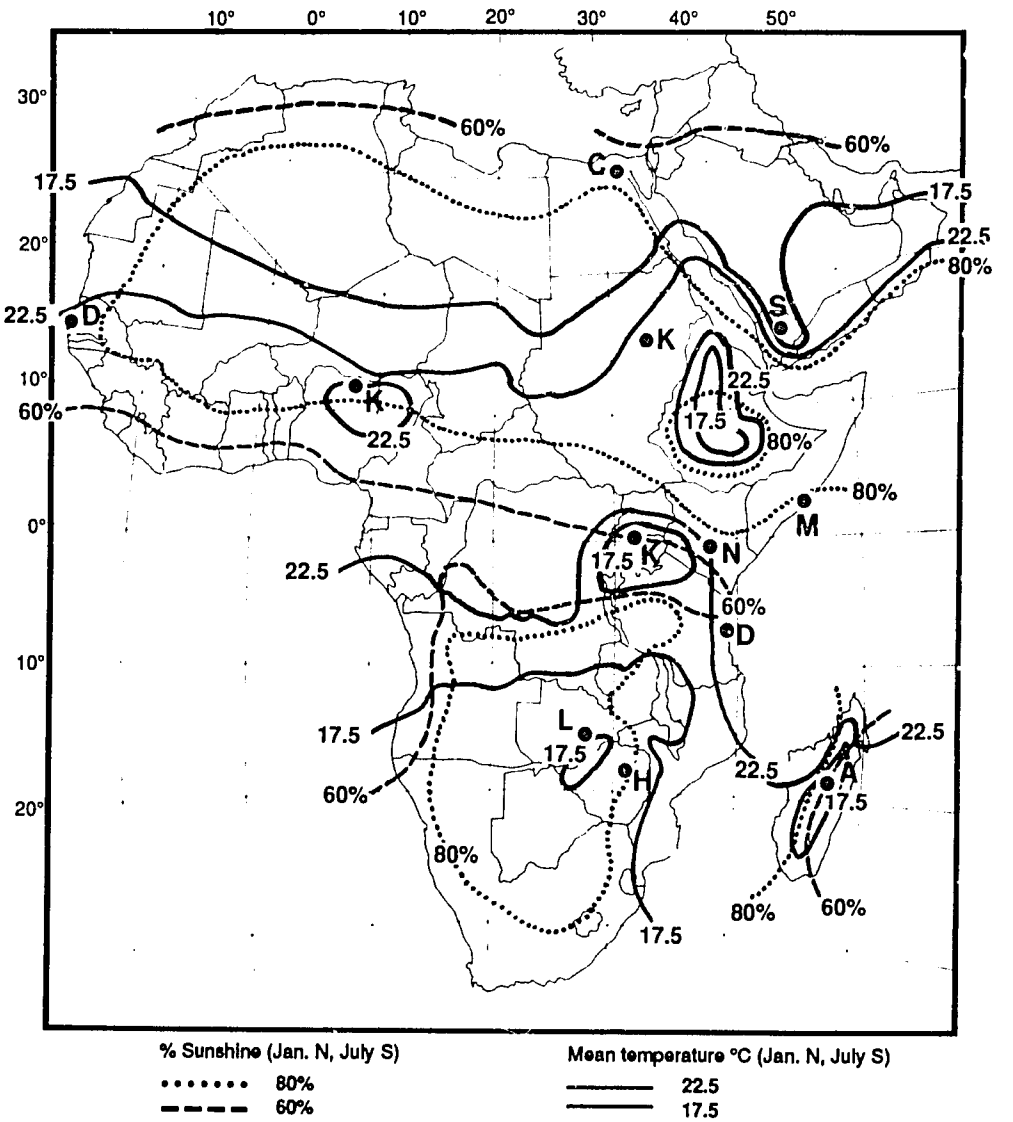

Figure 1. January (July in Southern Hemisphere) mean temperature and average % sunshine for Africa. Source: FAO agroclimatological data.

extends to some of the adjacent temperate regions—warmer parts of the high rainfall, temperate mega-environments (ME2 and ME3, the latter with acid soils). More importantly, especially in Asia, we must not overlook hot locations where wheat grows with a limited water supply. This typically involves seeding on residual moisture from the summer monsoon, following either a summer fallow period (heavy soils of central India) or a summer upland crop or paddy crop (e.g., Bangladesh, Burma, Thailand). Sometimes winter showers occur or partial irrigation can be given early in the life cycle, but most of the crop's water supply is residual moisture stored in the root zone before seeding. Soil type and hence rooting depth and storage capacity are key issues. We put this wheat environment into our dry, residual moisture mega-environment (ME4C, less than about 500 mm of water for the crop). This environment seems to be of increasing importance for wheat in hot areas (e.g., Bangladesh) and offers much potential for area expansion.

Thus, nontraditional, warm environments for wheat comprise all of ME5A and ME5B, most of ME4C, much of ME3 (due to the fact that most acid soils are within tropical latitudes), and small parts of ME2. Whether these divisions help the deployment of resources will depend on what the breeders and agronomists have learned, but obviously the demands must be met for disease resistance in ME2, ME3, and ME5A and acid soil tolerance in ME3. Also, it should be pointed out that wheat in temperate environments is often

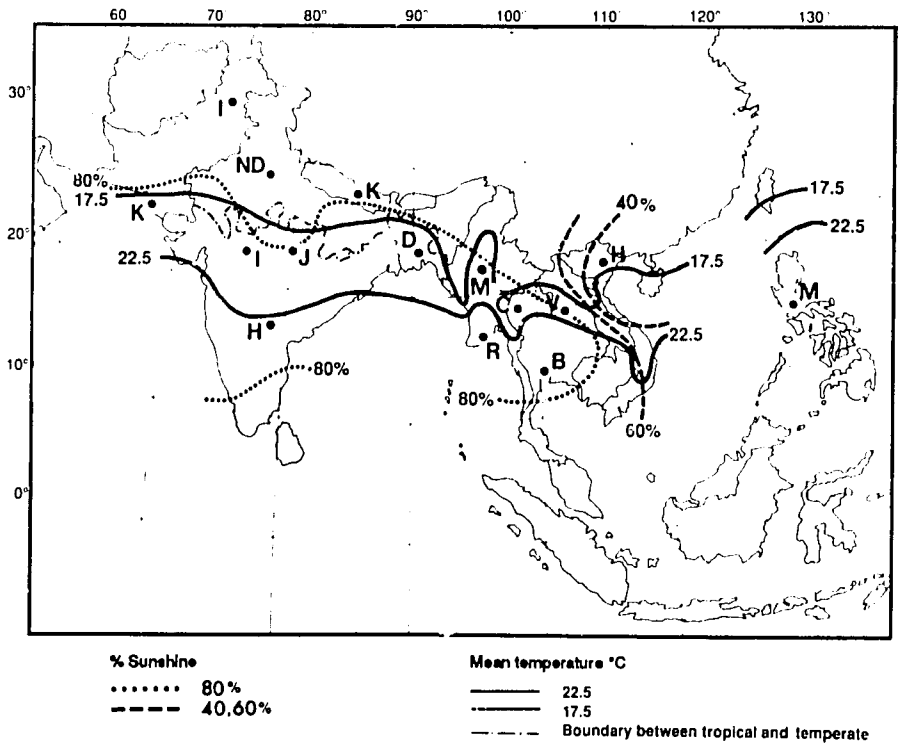

Figure 2. January mean temperature and average % sunshine for Asia. The boundary between tropical and temperate zones in India is also shown. Source: FAO agroclimatological data.

exposed to super optimal temperatures, for example in warm years and especially during grain filling and with late sowings, and to warmer area diseases (e.g., *Helminthosporium* spp.). This and the possibility of global warming suggest beneficial spillover effects from wheat research in warmer environments and indicate that the divisions established here are actually lines across a continuum.

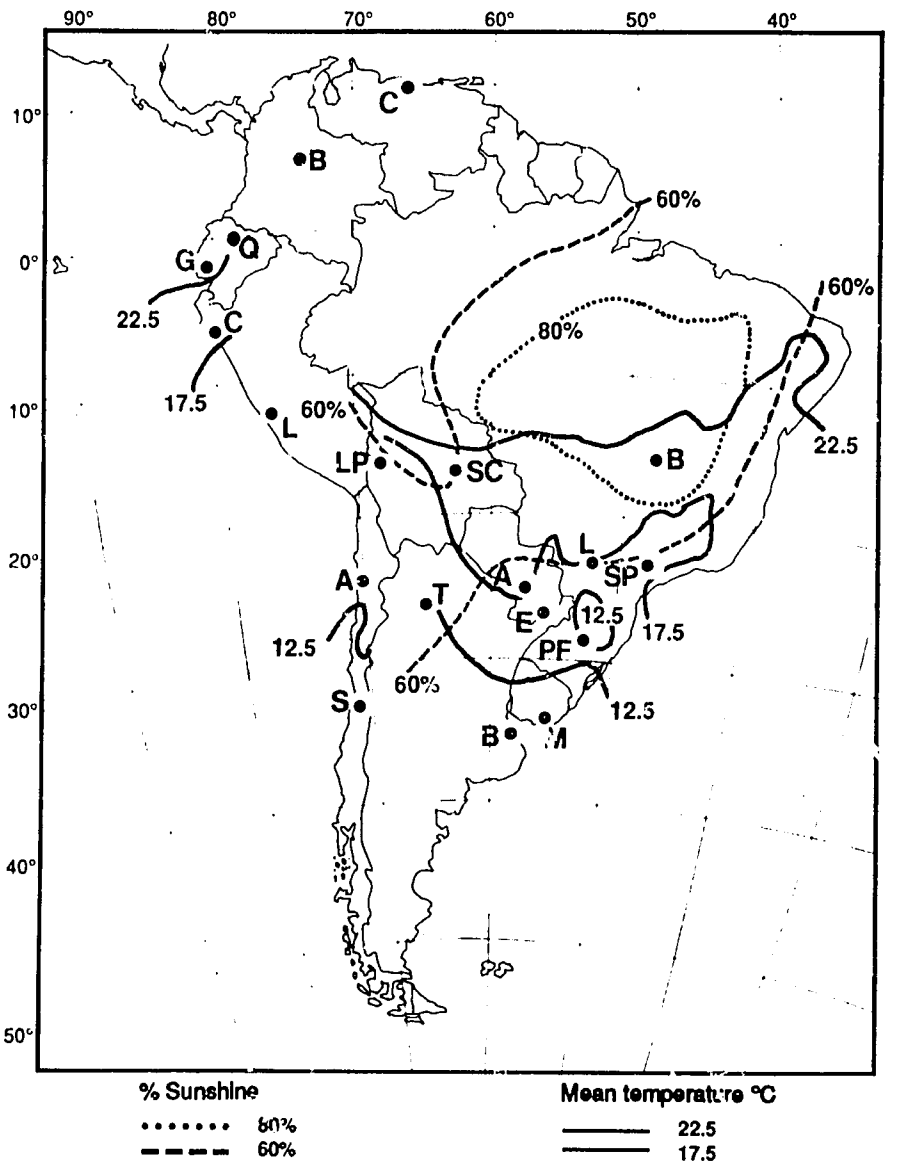

Figure 3. July mean temperature and average % sunshine for Latin America. Source: FAO agroclimatological data.

Overview of Trends in Wheat Production, Consumption, and Imports in Tropical Countries

General trends in the world wheat economy

Research priorities for tropical wheat must be set in the context of longer term trends in the world wheat situation. Since most wheat consumed in tropical countries is imported, expectations about wheat prices in world markets over the long term have an important bearing on decisions regarding domestic wheat production.

World wheat prices on a real basis have been declining at 1% annually for many decades (Figure 4). Also at this moment in 1990, the world wheat harvest is expected to set a new record of nearly 600 Mt (million tons), some 10% above last year's record. Nonetheless, world grain stocks have recently been at historically low levels. In addition, in the 1980s the rate of increase in wheat production has slowed significantly since the 1960s and 1970s (Figure 5). During several years in the late 1980s, world wheat consumption exceeded production. Does this mean that in the 1990s we might enter a new stage of world food shortages that would reverse the long-term tendency for real price decline? We doubt that this reversal will occur, but several factors point toward a slowing of growth in world cereal production to the year 2000 and beyond.

- The developing world has experienced an extraordinary period of rapid growth in cereal production, especially in wheat, stimulated in large part by the seed-fertilizer revolution in Asia (Figure 5). After 25 years of rapid change, the easy gains have been made, and future yield increases are unlikely to match their recent performance. For example, the world's largest wheat producer, China, after rapid production increases from 1978 to 1984, has seen a relative stagnation of yields in the remainder of the decade of the 1980s. The area under cereals in China is now in decline as land is switched to higher valued crops and nonfarm uses.

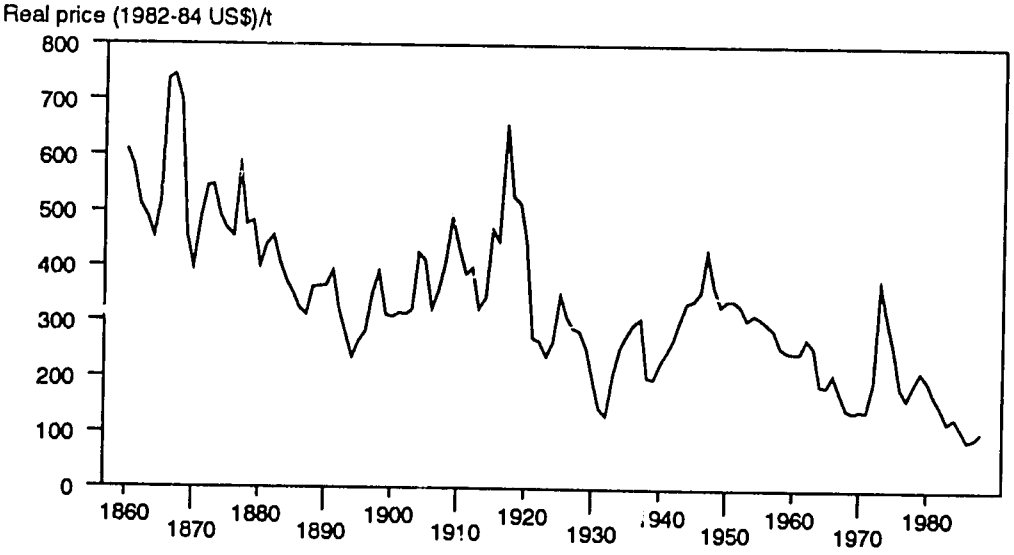

Figure 4. Change in real wheat prices since the mid-1800s. Source: U.S. Bureau of Census.

- The negotiations of the Uruguay round of the GATT (General Agreement on Tariffs and Trade) are due to be completed in late 1990. If the Cairn's group of countries and the USA are successful in these negotiations, export subsidies for wheat and other agricultural products would be phased out over the next few years. Since all the large exporters (except Australia and Argentina) subsidize wheat producers by about 50%, removing subsidies would lead to an increase in world wheat prices of 0-35% (Sarris 1989, Dixit et al. 1989). (The estimates vary depending on the economist whom you talk to, but all indicate an increase in world grain prices).

- Heightened environmental concerns in the developed market economies have already led to withdrawal of some fragile land from production (especially in the USA) and pressure is increasing for reductions in the use of farm chemicals, especially in the European Economic Community (EEC). These factors may lead to some reduction in wheat supply in major exporting countries, or at least to a diminished ability to respond to higher world prices as has occurred in previous food crises.

Against these somewhat bullish predictions for price recovery, the growth of food demand, including demand for wheat, is also slowing, due to slowing population growth and the fact that some major countries such as China have already reached high levels of cereal consumption. Overall, the annual growth in wheat demand is nonetheless expected to be near 3% in developing countries for the next decade or so. Another issue is the USSR, the world's second largest wheat producer and largest importer, which is undergoing policy reforms that may have effects similar to those of the Chinese reforms of the late 1970s that led to increased local wheat production. For example, the USSR recently doubled the producer and consumer prices for wheat and is also providing a bonus for increased production in the form of payment in foreign exchange.

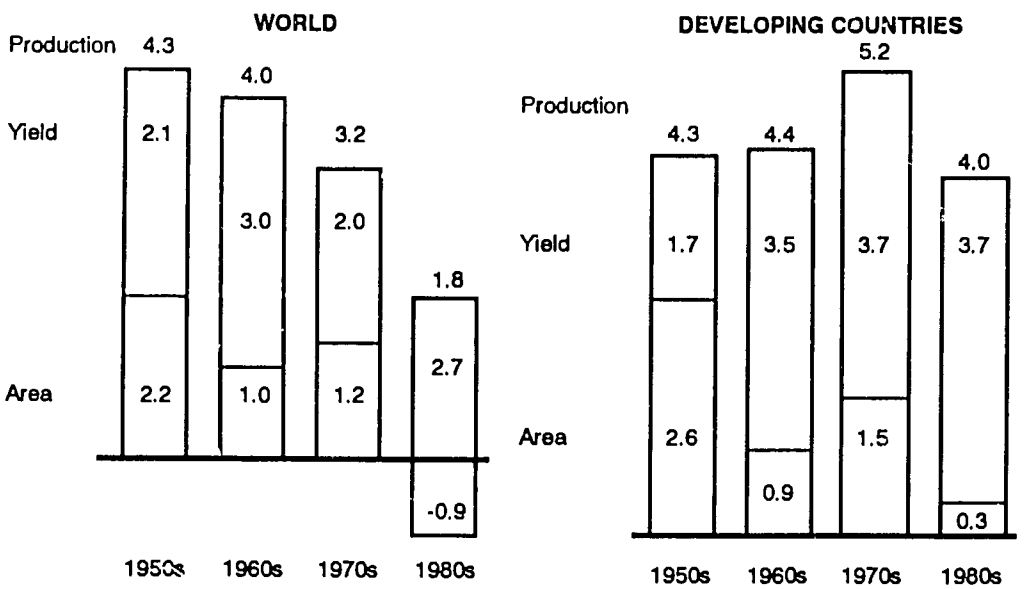

Figure 5. Growth rate (%/year) of wheat area, yield, and production for the world and developing countries. Source: FAO data tapes.

On balance, the evidence points to a tighter grain market in the 1990s. However, this forecast is subject to many uncertainties (especially in China and the USSR) and the situation needs to be closely monitored by wheat scientists and research administrators.

Trends in wheat in tropical countries

Byerlee (1985) provides an overview of trends in wheat production and consumption in tropical countries up to the early 1980s. Our purpose here is to refine and update those estimates.

Although we may agree on a working definition of "tropical wheat", the definition of a "tropical country" is complicated by the heterogeneity within countries. Brazil is a good example. Wheat is largely produced in the southern states of Rio Grande do Sul and Paraná, where temperatures are cooler than the temperature range given in the accepted CIMMYT definition of a tropical production zone. Nonetheless, wheat area in Brazil is expanding in the warmer tropics. In addition, most of the wheat consumed in Brazil is by people who live in tropical areas. Hence, in the following discussion we generally define Brazil as a tropical country. Likewise, wheat in India is produced under a wide variety of conditions, from temperate climates in the Himalayan foot hills to the hot areas of central and southern India. For most of the statistics provided below, we have separated out the hot areas by defining wheat production in the central and southern states as tropical. Hence the tropical countries include all of sub-Saharan Africa (except Lesotho and Swaziland). In Asia we include Yemen, all of southeast Asia, and the Pacific from Burma to Fiji; Bangladesh, Sri Lanka, and the States of Madya Pradesh, Maharastra, Gujrat, West Bengal, Orissa, and Karnataka in India. In Latin America, we include all countries from Guatemala south to Brazil and Paraguay.

The tropical countries as a group account for 35% of the world's population, but currently produce 15 Mt or less than 3% of the world's wheat (Tables 1 and 2).

Table 1. Distribution of world population and wheat area, production, and consumption by tropical and nontropical regions, 1986-88.

Regions	Population (%)	Area (%)	Production (%)	Consumption (%)
Total tropics	35	5	3	8
Total nontropics	65	95	97	92
World	100	100	100	100

Source: FAO data tapes.

Table 2. Wheat area, yield, and production in tropical regions, 1986-88.

	Area (M ha)	Yield (t/ha)	Production (Mt)
Africa	1.14	1.48	1.69
Tropical India	5.29	1.19	6.27
Other tropical Asia	0.73	1.88	1.37
Brazil	3.60	1.62	5.82
Other tropical Latin America	0.31	1.18	0.37
Total	**11.06**	**1.40**	**15.52**

Source: FAO data tapes.

Their total wheat consumption is 40 Mt (8% of the world total), so that over 60% of the wheat consumed in tropical countries is imported (70% if tropical India is excluded) (Table 3). Currently, over 40 countries in the tropics consume over 100,000 t of wheat while only 10 countries produce that amount.

Most of the wheat production in the tropical countries occurs outside the tropical areas, either in the highlands (e.g., Ethiopia) or in higher latitudes (e.g., Brazil). Hence of the 15 Mt produced in these countries, only about 8 Mt is actually produced in tropical areas (> 17.5°C in the coolest month), with by far the largest amount in India (6 Mt). Bangladesh, Burma, and the Sudan also have significant areas sown to wheat under warm to hot conditions.

Figures 6 to 10 and Table 4 provide an overview of wheat production and consumption trends in tropical countries, grouped by region. In sub-Saharan Africa, where nearly all countries are classified as tropical, wheat consumption is now growing more slowly compared to the high growth rate of the 1960s and 1970s (Byerlee and Morris 1990) (Figure 6). This reflects the particularly difficult economic situation in this region, which has led to declining imports and, in the case of Nigeria, the largest wheat consumer, a complete ban on imports (Olugbemi 1991).

Table 3. Wheat consumption and imports in tropical regions, (1986-88 average).

Tropical region	Consumption (Mt)	Per capita consumption (kg/yr)	Net imports (Mt)	Percent wheat imported
Africa	5.85	13	4.16	71
Tropical India	10.84	24	4.57	42
Other tropical Asia	8.82	16	7.45	86
Brazil	7.81	55	1.99	25
Other countries in tropical Latin America	6.86	48	6.49	95
Total	**40.09**	**23**	**24.58**	**62**

Source: FAO data tapes.

Table 4. Growth rates in per capita wheat consumption in tropical regions.

Tropical region	Growth rate (%/year) 1961-70	1971-80	1981-88
Africa	3.5	2.9	-1.8
Tropical Asia	9.1	3.7	0.1
Brazil	1.8	6.2	1.2
Other countries in tropical Latin America	2.0	1.2	0.9
All	**4.1**	**3.4**	**0.5**

Source: FAO data tapes.

Wheat production in the region has grown more slowly than consumption and gains in both area and yields have been modest. Over 70% of the wheat consumed in tropical Africa is imported.

In tropical Asia, consumption has also levelled off in the 1980s (Figure 7). This, in part, reflects the fact that Bangladesh was unable to sustain the rate of gain in production that it had experienced from 1973 to 1982. However, production continued to increase in tropical India largely due to the effects of expansion of irrigated area in central and southern India. Including tropical India, this region has the highest rate of self-sufficiency in wheat of 40%.

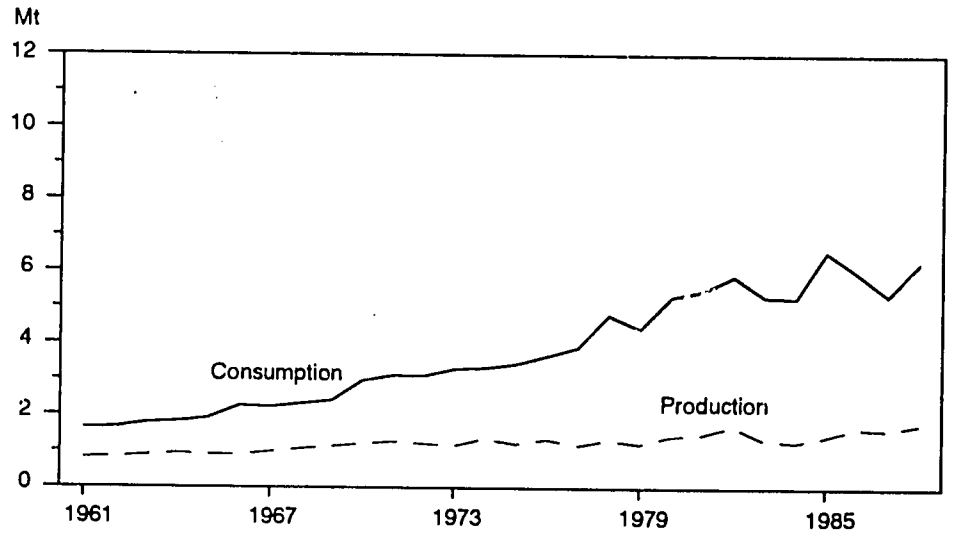

Figure 6. Growth of wheat consumption and production from 1961 to 1988 in sub-Saharan Africa. Source: FAO data tapes.

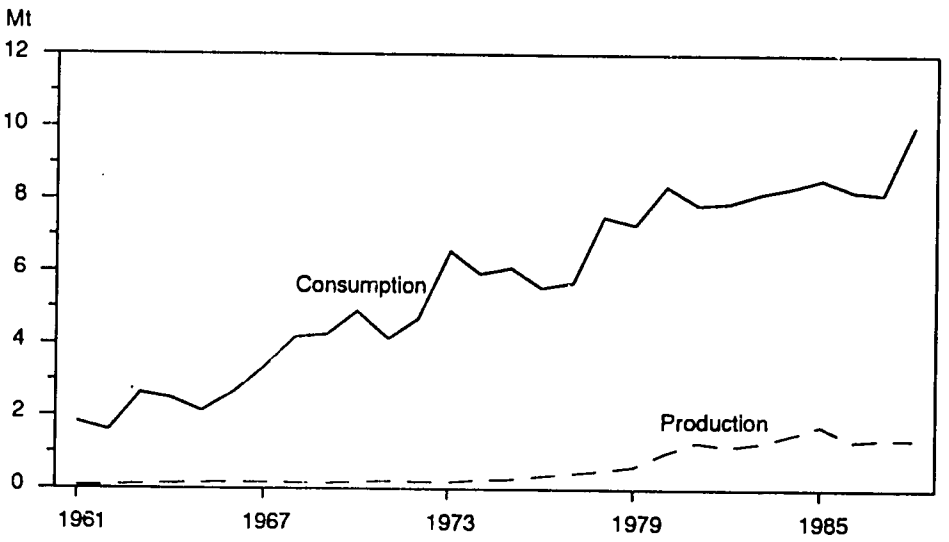

Figure 7. Growth of wheat consumption and production from 1961 to 1988 in tropical Asia (excluding tropical India). Source: FAO data tapes.

In tropical Latin America (excluding Brazil and Paraguay for the moment), wheat consumption continued to increase in the 1980s at a steady rate (Figure 8). At the same time, production reversed the downward trend established in the 1960s and 1970s, when wheat area in the Andean countries declined sharply. Over 90% of the wheat consumed in tropical Latin America is imported.

By contrast, in Brazil and Paraguay, where most wheat is produced under relatively warm conditions, production experienced a dramatic expansion in the 1980s (Figures 9 and 10) so that imports fell off sharply. Wheat has actually been exported from Paraguay in recent years (Pedretti and Kohli 1991). The success of these two countries reflects rapid

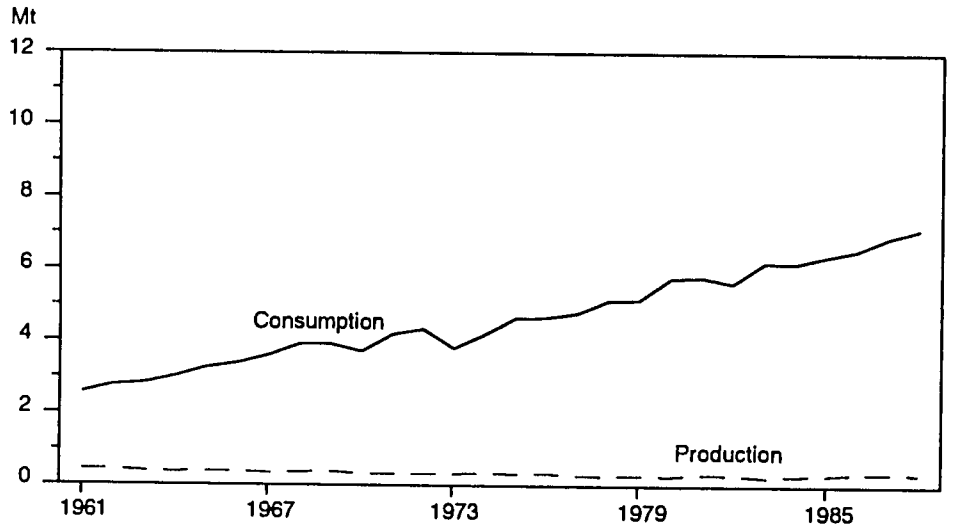

Figure 8. Growth of wheat consumption and production from 1961 to 1988 in tropical Latin America. Source: FAO data tapes.

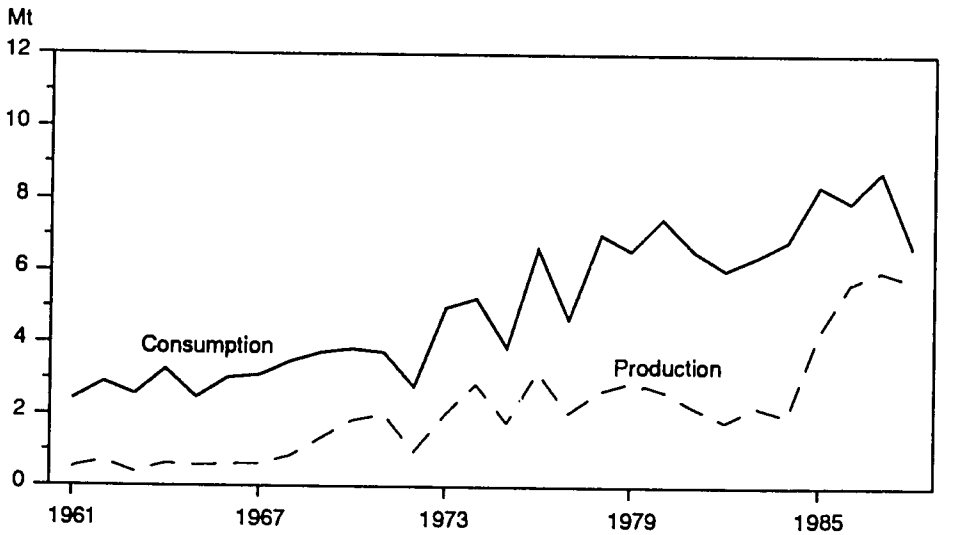

Figure 9. Growth of wheat consumption and production from 1961 to 1988 in Brazil. Source: FAO data tapes.

technical progress in increasing wheat area and yields aided by supportive credit and price policies.

Managing growing wheat consumption in the tropics

During the 1984 Conference in Mexico on Wheats for More Tropical Environments, it was stressed that an integrated policy toward rising wheat consumption and imports in the tropics should give equal consideration to policies to manage demand, especially since several key policy distortions, such as price subsidies on bread, were responsible for the rapid increase in wheat consumption in the 1970s (Byerlee 1985). In the 1980s, there has indeed been a significant slowing in the rate of growth in per capita wheat consumption in all regions (Table 4). In Africa, per capita wheat consumption has fallen after rapid increases in the previous two decades. This only in part reflects an overall decline in food consumption in Africa. In addition, the slowing of growth in wheat consumption in all tropical regions reflects measures taken in the 1980s to discourage further substitution of wheat for traditional food staples in the diet. Three such measures are bread pricing policies, food aid, and the use of composite flour for making bread

Bread pricing policies—Although it is often stated that bread consumption in tropical countries inevitably increases as incomes and urbanization rise, a more important and overlooked factor promoting wheat consumption has been the low and decreasing price of bread relative to traditional staples. Lower prices are brought about by a) trade and exchange rate policies and b) bread subsidies to consumers. Thus, in Africa and Latin America, policy distortions, which became pervasive in the 1970s, have been reduced in many countries under the policy reforms of the 1980s. In particular, exchange rates have been devalued in real terms by about 50% in a large number of African and Latin American countries (Byerlee and Sain 1990, Morris and Byerlee 1990). Exchange rate devaluation has led to a sharp increase in the price of imported staple foods such as wheat in tropical countries. At the same time, several countries have removed consumer subsidies on bread (e.g., Brazil, Ecuador, Bolivia) and this

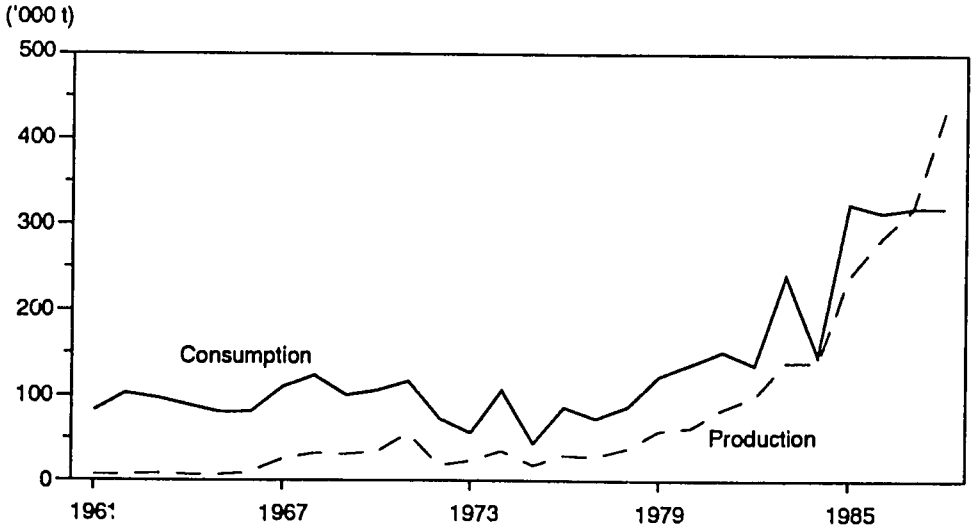

Figure 10. Growth of wheat consumption and production from 1961 to 1988 in Paraguay. Source: FAO data tapes.

has resulted in an increase in the price of bread relative to other staples (Figure 11). In contrast, in southeast Asia policies have traditionally discriminated against wheat consumption.

Food aid—Food aid in the form of wheat tends to encourage substitution of bread for traditional staples (Byerlee 1985). In the 1980s, food aid for tropical countries has switched somewhat from wheat to other commodities such as rice and sorghum. Nonetheless, food aid has sustained wheat consumption in sub-Saharan Africa and in tropical Latin America (Figure 12). Wheat food aid accounts for over 50% of the total wheat consumed in eight countries in sub-

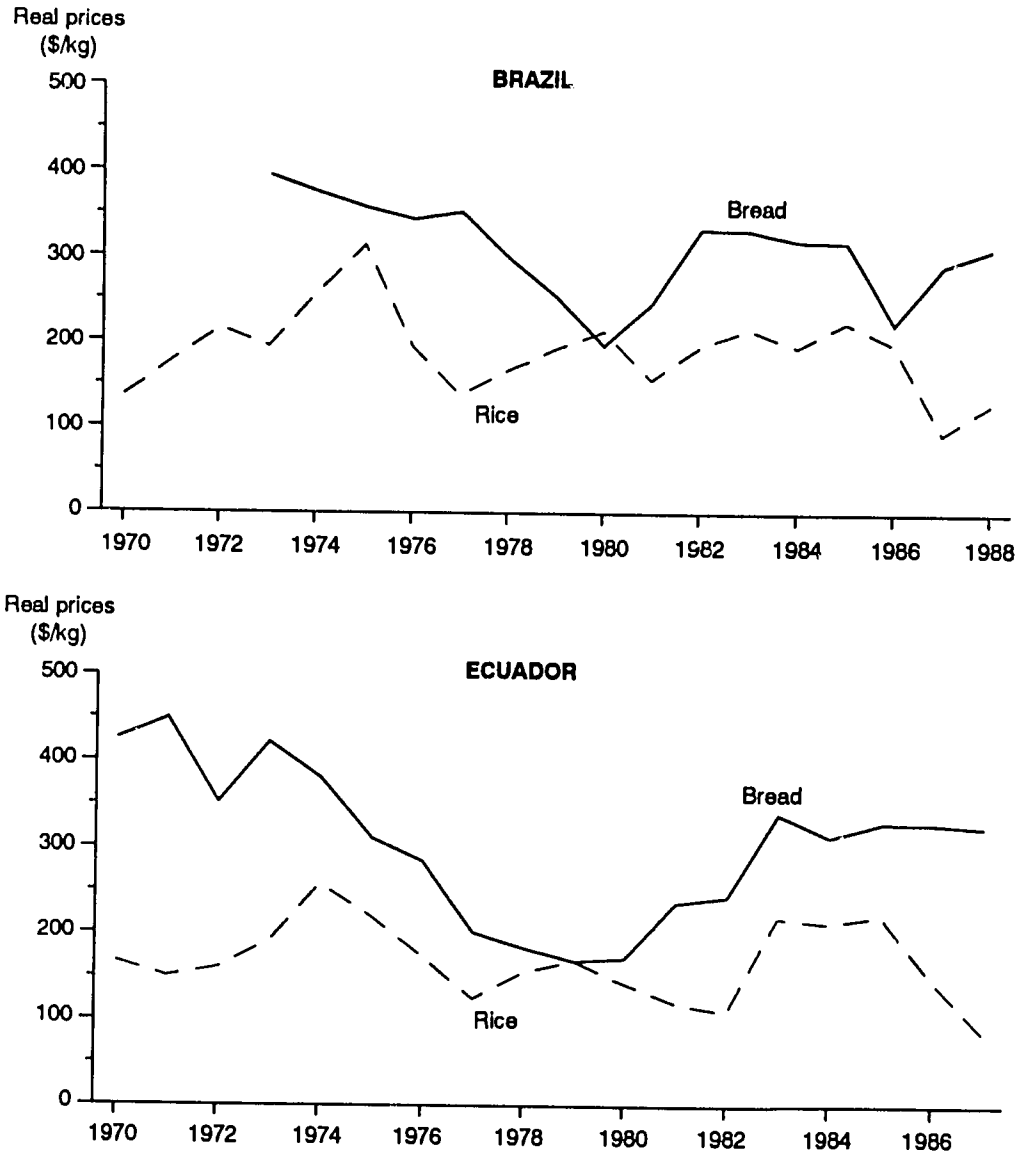

Figure 11. Change in real prices for bread and rice in Brazil and Ecuador, 1970-88. Base: 1980 = 100. Source: Byerlee and Sain (1990).

Saharan Africa, seven countries in tropical Latin America and the Andean zone, and only three countries in tropical Asia.

Composite flours—Several countries (e.g., Brazil, Sudan, Costa Rica, Nigeria) have attempted to implement programs to substitute sorghum, maize, and cassava flour for imported wheat flour in making bread. These programs had failed in the 1970s since imported wheat was often cheaper than local staples because of the policy distortions discussed above. However, even with a reversal of price policies, it seems that the costs of preparing composite flours, especially of converting equipment to mill local cereals, have been underestimated. Hence, the impact of these programs has been less than expected.

Developments on the Biological Front

We do not want to preempt the presentations that follow in this conference, but we would like to mention several interesting developments that have taken place since the 1987 conference in Thailand.

Regarding genetic resistance to biotic stresses, there has been a growing confidence in the durability of the resistances to stem rust and leaf rust, which is now found in much of the germplasm coming out of CIMMYT and some national programs. The genetic basis of these resistances, inevitably associated with partial resistance genes and the slow rusting phenomenon, is gradually being clarified. In the case of spot blotch, *Helminthosporium sativum*, there has also been notable progress. Good levels of *Helminthosporium* resistance are being incorporated into high yielding plant types by breeding programs in Brazil and Zambia and CIMMYT as well. This resistance has come from both Chinese wheats and the wild species *Agropyron curvifolium*. Regarding *Fusarium*, sources of resistance from Chinese wheats have been incorporated into better high yielding plant types and are showing excellent promise under artificial inoculation in Encarnacion, Paraguay. Also, Canadian researchers have transferred genes for tolerance to the *Fusarium thrichothecene* toxins from protoplasts of a resistant Chinese cultivar to those of a susceptible Canadian one (J.D. Miller, pers. comm.).

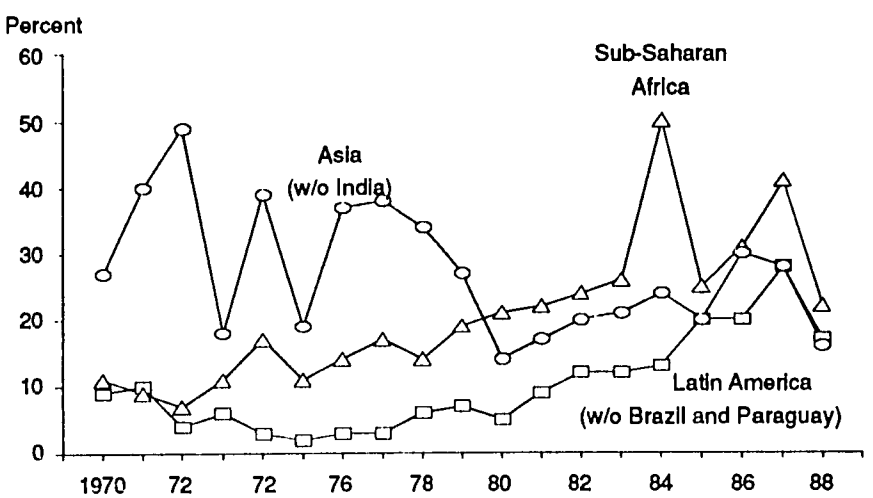

Figure 12. Wheat food aid as a percentage of consumption in tropical regions.

Thus, even the so-called intractable tropical diseases of wheat are starting to yield ground in the face of sustained research efforts that employ both traditional and more novel tactics to develop genetic resistance (the key word in all of this being "sustained"). We must continually remind research administrators that, given the resources, plant breeders and pathologists can solve many of these disease problems. New techniques will help, but sustained support is more critical.

Turning to abiotic stresses, heat and, to a lesser extent, drought are the principal ones. Regarding drought, there has been little genetic progress related to plant growth on residual moisture. The famous Indian variety C306 (released in 1967) and local durum varieties continue to dominate in the hot rainfed areas of central and southern India. The superiority of C306 appears to be related to its excellent biomass production and outstanding maintenance of spike and kernel number/m^2 under drought (Aggarwal and Sinha 1987); this is possibly related to a longer vegetative cycle and deeper root system. Under these harsh conditions, it is also important to have adaptation to early planting in hot soils, often at considerable depth. However, even without progress in this area, we are learning from experience—especially on the favorable deep silty soils of Bangladesh—that, with early planting, good agronomy, and some winter showers, very respectable yields can be obtained without irrigation using modern semidwarf varieties. During 1989-90 in the Dinajpur District of Bangladesh, the highest yield in yield maximization demonstrations without irrigation (but with 100 mm of rain soon after planting) was 5.3 t/ha—only 13% behind the best yield resulting from irrigation (D. Saunders, per. comm.). Also, farmer-managed plots of no-till rainfed wheat, simply broadcast into the maturing paddy rice just before harvest, were observed to yield more than 3 t/ha in the Kushtia District further to the south.

With respect to tolerance to high ambient temperatures, we have moved slowly toward identifying superior genotypes; selecting directly for traits conferring such tolerance is still on the horizon. Experience points toward some consistently superior genotypes in irrigated, hot dry (disease-free) regions (Debeira in Sudan, Chenab 70 in Ethiopia, Fang 60 in Thailand, Trigo 3 in the Philippines), but the basis of this adaptation is not well understood. Researchers in Australia using the Canberra phytotron have just completed a very thorough search for genotypic differences in sensitivity to high temperatures (30-25°C versus 18-13°C) during booting (Dawson and Wardlaw 1989) and during grain filling (Wardlaw et al. 1989). Results were rather variable and appeared to interact with radiation level; also high humidity (low VPD) enhanced the depression of grain number with high temperature. Nevertheless, some consistent patterns were revealed: European wheats were more sensitive to high temperatures (47% reduction in grain number with booting heat, 46% reduction in kernel weight with grain filling heat) than were wheats from the Middle East (22 and 32% reductions, respectively), or from the Philippines (14 and 30% reductions, respectively).

The recent work of Kuroyanagi and Paulsen (1988) provides another interesting result that may help in our understanding of adaptation to high temperatures. They showed that kernel growth and senescence in wheat were influenced more by high temperature during grain filling if the heat was applied to the roots rather than to the shoots; they suggested that cytokinin flux from the roots may be reduced directly by high temperatures. A second interesting and

quite unrelated discovery has been the recent detection of evidence for intermediate C3-C4 photosynthesis in wheat spikes (Ziegler-Jons 1989). This discovery may be related to the demonstration by Blum (1986) that wheat awns have a much higher optimum temperature for photosynthesis than do the glumes or leaves (and also a much higher water use efficiency). Blum recommended that large awns are desirable for adaptation to hot and dry conditions.

Finally, improved crop management techniques are resulting in some extraordinary wheat yields under irrigated, very hot and dry conditions. For example, yields of 5 t/ha have been reported for the Awash Valley of Ethiopia (January mean 23°C, Mohammed 1989) and in Karnataka in southern India (January mean 24°C, Hanchinal 1988); a yield of 6 t/ha in 1989-90 season was recorded in a farmer's field in Gezira, Sudan. How is this possible when the simple empirical model used by Fischer (1985) predicted yields of 3 t/ha under such conditions? Also, putting Wad Medani (Sudan) weather data for 1989-90 into the CERES (Crop Estimation through Resources and Environmental Synthesis) wheat simulation model resulted in a maximum yield of only 3 t/ha (M. Bell, pers. comm.)—the exact circumstances under which a farmer achieved 6 t/ha! Even the simple functions derived from the Aggarwal and Penning de Vries (1989) wheat model, about which we shall here more later during the conference (Aggarwal 1991), only predict about 4 t/ha.

It seems that we are seeing in the field what Rawson (1988) observed in hot controlled environment conditions, i.e., a yield of 11 t/ha in 80 days under a 34/16°C temperature regime with 24 MJ/m^2/d total short wave radiation (a Gezira, Sudan-like climate), plus abundant nutrition and water provided via a hydroponic root medium. Is nutrition and water supply the whole answer? Certainly, it appears from the field studies to be very critical, but how come our models, which assume unlimited water and nutrients, are so off the mark? This is quite an intriguing situation that must give us more optimism about yield prospects in hot areas, but which also demands more research. We offer just two hypotheses:

- Evaporative cooling of transpiring leaves—under conditions of dry air and high radiation, water, and nitrogen supplies, hence high stomatal conductance —is such that the crop canopy is much cooler than the air temperature. This cooling effect is mostly a function of the VPD of the air. At the hottest time of the afternoon for an average January day in Wad Medani (Sudan), air temperature is 33.5°C and its VPD is 43 mb. Extrapolating the wheat minimum stress base line of Idso (1982) predicts a sunlit leaf temperature of 23°C—10.5° lower than the air temperature. If this effect is carried through to the temperature of the growing point or spike, development rates should be less and yield potential greater than can be predicted from air temperature alone. This would be a phenomenon confined to hot dry locations with irrigation (ME5B). It may explain why yields are more closely associated (negatively) with minimum temperature than maximum temperature in hot locations (Mann 1985). Similar reasoning (cooling the shoot apex) may explain why a mulched (and/or continuously wet) soil surface is beneficial early—before full cover is established, as has been observed in experiments this year in Thailand. However it doesn't explain the results of Rawson (1988) above where there was no slowing of development associated with his remarkable yields. This prompts a

second hypothesis, which alone or in combination with the first, could be involved.

Several papers (see summary of Ludlow et al. 1989) have pointed to root signals produced in the presence of soil mechanical impedance that inhibit top growth and stomatal conductance. Regardless of evaporative cooling and canopy shading, soils—and hence wheat roots—will be warmer in hot locations. Kuroyanagi and Paulsen (1988) have already indicated some deleterious effects of root warming in wheat. Perhaps the negative effect of mechanical impedance is somehow magnified under warm soil conditions, and Rawson's results could be attributed more to the absence of mechanical impedance (he used a porous gravel bed) rather than, or as well as, to the abundant nutrients and water. In fact, if the effect of mechanical impedance is sensed in proportion to the relative reduction in potential root growth rate (presumably related to temperature), a temperature by impedance interaction of this type would be plausible.

Both of these hypotheses point to the importance of crop agronomy in order to reach maximum yields. What is not clear yet, however, is the relative importance of an abundant supply of water and nutrients (particularly nitrogen), other measures to reduce the temperature of the growing point (deep seeding, surface mulching, rapid canopy cover), and reduced mechanical impedance. Answers to these questions will influence the efficiency of input use and cost of growing wheat in hot climates.

Even given our present lack of understanding, it does not appear that the efficiency of use of water and nitrogen by wheat in warmer areas can be as high as is achieved in temperate locations. Efficiency considerations of wheat and some alternative winter crops in warmer areas are summarized in Table 5. The water use efficiency of wheat should exceed that of rice—one alternative winter crop in some places—although wheat's nitrogen use efficiency may not exceed that of rice. The possibilities of unforeseen drought (interruption in water supply) and brief cool spells (minimum temperatures below 15°C for rice and

Table 5. Alternative winter crops to wheat in nontraditional, warm areas.

Crop	Advantages[a]	Disadvantages
Rice	Staple food High NUE	Low WUE Sensitivity drought, cold
Maize	High WUE High NUE	Often not staple food Sensitive drought
Sorghum	High WUE High NUE	Often not staple food Sensitive cold, birds
Winter pulse (lentil, chickpea)	N fixation High value	Low yielding Sensitive weeds
Winter oilseeds (Brassicas)	High value Break crop	Low yielding Sensitive management
Vegetables	High value Labor intensive	Marketing risks Sensitive management, drought

[a] WUE = water use efficiency; NUE = nitrogen use efficiency.

sorghum, 5°C for maize) make wheat a very competitive cereal crop in many of these nontraditional, warmer areas. Winter pulses (lentils, chickpeas) and oilseeds (*Brassicas*) do, however, offer viable alternatives in many of these situations. Another task for agronomists, therefore, is to examine cropping systems that integrate these crops with wheat because the rotation of broad leaf and gramineaceous crops offers complementary opportunities.

Assessing the Economics of Growing Wheat in Warmer Areas

Common myths about the benefits of domestic wheat production

Most countries that seek to expand wheat production into the warmer tropics use two reasons to justify these efforts: food security and saving foreign exchange (Morris and Byerlee 1990).

To try to maintain food security, governments are often reluctant to depend excessively on imported wheat because instability in world wheat prices exposes consumers (or the state treasury) to sharp fluctuations in foreign exchange outlays. We do not find this argument very convincing. Wheat production in tropical areas is subject to substantial year-to-year fluctuations because of numerous factors, including high and variable temperatures, water shortages, and sensitivity to management, especially date of planting. Consequently, the average coefficient of variation (CV) of wheat yields in tropical countries, at about 19%, is significantly higher than in most traditional wheat producing countries, even those that produce wheat largely under dryland conditions (CV=14%) (Singh and Byerlee 1990). Hence, the CV around the trend for wheat yields during the 1968-88 period is 36% in the Sudan, 21% in Tanzania, and 37% in Brazil, compared to the CV of 27% for world wheat prices over the same period. Import substitution programs for wheat may increase rather than decrease instability in food availability.

The second argument often made in favor of promoting domestic wheat industries in tropical countries is to save the scarce foreign exchange presently spent to import wheat. In analyzing foreign exchange effects of domestic wheat production, two issues should be noted. First, domestic wheat production uses foreign exchange *directly* in the form of imported machinery and purchased inputs. In many capital-intensive wheat production schemes, at least half of the foreign exchange savings realized from reduced wheat imports is spent on imported production inputs (e.g., machinery, fuel, fertilizer, crop chemicals). In extreme cases, where wheat yields are low and use of imported machinery and inputs is high, domestic wheat production may actually use more foreign exchange than is saved. Second, even if wheat production has a net positive effect on foreign exchange, *indirect* costs in foreign exchange savings must be considered. For example, the same resources used to produce wheat might be used instead to produce cotton for export to generate foreign exchange, or to produce another food crop better adapted to the local production environment. The critical policy question is not simply whether wheat production saves foreign exchange; the key question is whether wheat production is *most* efficient among available alternatives in saving or generating foreign exchange.

Key factors determining the efficiency of wheat production in the warmer tropics

The efficiency of using resources to produce wheat must, therefore, be measured in terms of its contribution to national income and to saving foreign exchange relative to competing crops. Also, to be viable, wheat production must

be economically attractive to farmers. These two conditions do not always coincide. For example, Saudi Arabia has made wheat production so attractive to farmers that it is now a significant wheat exporter, even though from a national viewpoint it is doubtful that it is efficient to use scarce water resources to produce wheat. In other cases, such as Ecuador, it may be quite efficient for a country to produce wheat, but policy distortions have made it unattractive for farmers to grow the crop (Byerlee 1989).

Clearly the warmer tropics are characterized by a wide variability in agroclimatic and economic conditions, and it is impossible to make general statements about the efficiency of wheat production in all these environments. However, a number of studies conducted in collaboration with CIMMYT and by others suggest that several factors are often critical in determining the efficiency of wheat production in these environments.

Wheat yields—Average yields of wheat obtained by farmers in the tropics are still under 1.5 t/ha. These low yields are to be expected in dryland conditions where input use is very low. For example, it is estimated that in central India a yield of only 0.3-0.4 t/ha will cover costs of dryland wheat production, given the very low level of inputs applied. However, low yields under irrigated conditions, where infrastructural costs and input levels are much higher, is a problem in many irrigated crop production schemes in Africa and, to a lesser extent, India. Given the increasing experimental evidence that yield potential is much higher than previously thought, efficient wheat production requires more attention to raising yields in the irrigated areas currently sown to wheat, rather than increasing the area under irrigated wheat. It appears that from what we have seen earlier, crop management will be the key to obtaining better yields in these areas.

Choice of production technology—The other side of the yield equation is the input costs for wheat production. Wheat in the tropics is produced under extremes of technology ranging from labor-intensive methods requiring over 100 person-days/ha (e.g., the small-scale systems of the East African highlands and South Asia) to highly mechanized methods using less than 20 person-days/ha (e.g., the large mechanized farms of Nigeria, Sudan, Zambia, Zimbabwe, and Brazil). A critical issue in many countries involves selecting a production technology that will maximize returns to scarce capital resources and provide employment opportunities for the poor. This issue is particularly critical in sub-Saharan Africa, where the relatively capital-intensive technologies that characterize many existing wheat production schemes are usually not cost effective.

The apparent financial profitability of some of these large-scale mechanized wheat production schemes is due to exchange rate overvaluation, which leads to underestimation of the true economic cost of imported machinery. Where exchange rate policies have been reformed to eliminate these distortions, the cost of mechanized wheat production has often increased dramatically, as occurred in Nigeria after the 1987 devaluation. Changing relative prices of labor and capital sharply decreased the profitability of wheat production on large-scale pump-irrigation schemes and provided strong incentives for small-scale production using less capital-intensive tubewell irrigation. For the same reason, Tanzania and Zambia, which in the past invested heavily in mechanized farms for producing rainfed wheat, now give more emphasis to production schemes based on labor-intensive technologies that appear to be economically efficient from the national standpoint. Likewise, the successful and efficient expansion of wheat in Kenya and probably the Sudan depends to a large extent on development

of small-scale technologies, especially for wheat harvesting and threshing (Longmire and Lugogo 1989).

Cost of irrigation—The construction of large-scale pump-irrigation schemes at a high price of about US$20,000/ha in sub-Saharan Africa, especially in Nigeria, has for the most part proven uneconomical as a means of promoting domestic wheat production. However, less costly and smaller scale systems in tropical India and Zimbabwe have been found to be quite efficient at reasonably high wheat yields. Even so, encouraged by highly subsidized electricity, the overexploitation of groundwater threatens the long-term sustainability of many of these schemes, especially in India.

Where an initial capital investment in irrigation infrastructure has already been made (e.g., Mali, Nigeria, Senegal, Sudan), there is a need to ensure its effective utilization, and to this end a cropping pattern including wheat may be appropriate. For this reason, it is important to distinguish between situations in which irrigation infrastructure is already in place (in which case capital investment costs can be considered sunk costs) and situations in which irrigation infrastructure has yet to be constructed (in which case capital investment costs must be included as a fixed cost). Sudan and Nigeria are examples of countries in which large-scale irrigation systems have already been constructed at great expense; although it would be difficult to justify constructing additional systems of the same type, efficient utilization of the infrastructure that is already in place requires an intensified cropping system that may include wheat, especially if yields can be increased.

Place of wheat in the farming system—The economic efficiency of wheat production often depends on where wheat fits into the overall farming system, since the opportunity cost of resources used in wheat production tends to be highly sensitive to competition from alternative crops. Especially in irrigated areas, the opportunity cost of using scarce land and water to produce wheat may be quite high, and high yields are needed for wheat to be an efficient crop. However, wheat can sometimes be introduced profitably in a rotation as an off-season crop, since this permits intensification of the farming system and leads to a reduction in the fixed costs associated with irrigation infrastructure. Also, wheat can often be a useful break crop in irrigated systems, as in the sugarcane schemes of southern India or the rice systems of Bangladesh.

In rainfed zones under residual moisture or limited irrigation water supplies, the opportunity cost of land and water resources is generally much lower, and wheat production may be efficient at quite modest yields of 1-2 t/ha. This was the situation underlying the rapid expansion of wheat grown under residual moisture after the rice crop in Bangladesh. Elsewhere in South and Southeast Asia, there is substantial potential to expand wheat production by growing the crop under residual moisture on land that is now left fallow in the cool season after the rice harvest.

Choice of production and consumption points—A final key factor determining the efficiency of wheat production is the location of production and consumption. Because internal transport and handling costs can be extremely high due to deficient transportation infrastructure, high fuel costs, and large distances between supply and demand points, especially in Africa, the spatial distribution of production and consumption can drastically affect the relative cost of producing wheat vs. importing it.

The case of Nigeria illustrates this point. In 1988, the landed price of imported wheat in the port city of Lagos was about US$220/t, but shipping this wheat to consumption centers in northern Nigeria added another US$110/t in transport costs. It appears that it was efficient (given current irrigation infrastructure) to produce wheat in northern Nigeria for consumption in northern Nigeria. However, shipping domestically produced wheat to Lagos would have added another US$110/t in transport costs, making local wheat much more costly than imports. A similar situation prevails in Tanzania, where most wheat is produced near Arusha, and transporting it to Dar es Salaam costs about US$60/t.

These examples illustrate the critical importance of defining production and consumption points in estimating the economic efficiency of domestic wheat production.

The need for economic assessment of the potential for wheat

Researchers are now more conscious of the importance of establishing whether a domestic wheat industry can be economically efficient. This is seen in the large number of economic studies on wheat in Africa in the 1980s (see Morris and Byerlee 1990). Nonetheless, economic analysis could be made more useful by paying more attention to the following points:

- More analysis to define the potential *range* of yields, costs, world prices, etc. under which wheat production would be efficient. This range would define the parameters within which wheat research and development efforts must operate in order to make wheat production efficient.

- More attention to looking not just at the economics of wheat production, but analyzing wheat as part of a farming system in which wheat may fill a niche. Also the economics of wheat production can only be assessed by considering the returns to crops that compete with wheat.

- More effort to define an efficient technology for wheat production, especially in terms of scarce capital and foreign exchange resources. For example, efficiency of wheat production in Africa requires the use of more labor-intensive harvesting techniques than the combine harvesters that are commonly employed in mechanized schemes.

Within these limitations there is increasing evidence that wheat production in the tropics can be profitable under a wide range of circumstances, especially if its major role is to increase cropping intensity in land that otherwise would not be cropped and if the production technology utilizes available labor resources rather than scarce foreign exchange in the form of imported machinery. For many irrigated wheat production schemes, the emphasis needs to change from increasing area sown to raising yields on the area already sown. Only when yields reach a threshold level defined as economically efficient, should area be expanded. This implies more agronomic research to define appropriate technologies and, because wheat is a new crop in much of the tropics, a strong extension effort to improve management at the farm level.

In large countries the emphasis should also be initially placed on producing wheat for local consumption in the production zone. Unfortunately, wheat mills are usually located in port cities, and successful local utilization of wheat may sometimes require the development of small-scale milling and processing facilities in the production zone.

Conclusions

World wheat supply may tighten over the next decade and this may encourage higher prices and production globally. Even so, growth of wheat consumption in tropical countries will likely be slower than before since policy distortions encouraging consumption have been reduced. The major exception is southeast Asia, where policies have not favored wheat consumption and where high economic growth and more open economies may lead to more rapid growth in wheat consumption.

Technical prospects for wheat in the winter season in tropical countries have been improved by:

- Evidence of higher yield potential than previously thought.
- Progress in disease resistance.
- Better understanding of the role of crop management.

There is good evidence that wheat can be economic in the nontraditional areas, especially at higher yields during the winter season and where opportunity costs arising from alternative winter crops are not high and appropriate technology is used.

We are cautiously optimistic that, with continued progress on the technical front and with reduced policy distortions, wheat production will gradually expand in the warmer nontraditional areas in the next decade under more realistic economic scenarios. But the emphasis should be on increasing yields in the already sown area.

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Resumen

Este trabajo examina la influencia de hechos biológicos y económicos recientes en los motivos económicos para tratar de lograr una mayor producción de trigo en zonas cálidas donde el cereal no es un cultivo tradicional. En el campo biológico, se observa un buen progreso en la obtención de mejor resistencia a las principales enfermedades, pero no se ha identificado con tanta claridad la resistencia genética a los factores abióticos desfavorables esenciales, a saber, el calor y la sequía. No obstante, el mejor manejo de los cultivos ha llevado a rendimientos inesperadamente altos (> 5 t/ha) en algunos sitios muy cálidos y secos pero irrigados, lo cual ha despertado cierto optimismo. Los aspectos económicos analizados incluyen la aminoración del crecimiento de la producción en países tradicionalmente productores de trigo, las actuales negociaciones del GATT (Acuerdo General sobre los Aranceles y el Comercio) sobre los subsidios a las exportaciones, la reducción del crecimiento del consumo en países tropicales en el decenio de los 80 como resultado de las modificaciones de las políticas impulsadas por la reforma económica y la dependencia continua de las importaciones (> 60%), gran parte de las cuales constituyen una ayuda alimentaria en Africa al sur del Sahara y en las zonas tropicales de América Latina.

Se examinan los aspectos económicos de la producción de trigo en zonas cálidas. Existen mejores perspectivas cuando el trigo contribuye a intensificar los sistemas de cultivo sin incurrir en un pesado costo de oportunidad en cuanto a divisas y cuando la producción no requiere un uso intensivo de capital. Dado el progreso previsto en el campo biológico, vaticinamos aumentos continuos de la producción de trigo en las zonas cálidas no tradicionales en el próximo decenio, en condiciones económicas más razonables como consecuencia de una menor distorsión de las políticas tanto en los mercados mundiales como a nivel nacional.

Trends, Potential, and Problems of Wheat Production in Tanzania

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Abstract

More than 80,000 t of spring bread wheats are being produced on about 60,000 ha on the mountain slopes and plateaus of the northern and southern highlands of Tanzania. Production has increased with the participation of large-scale state farms in the Hanang Wheat Complex despite several medium- and small-scale producers going out of wheat production. Should better wheat prices be offered and machines for harvesting be made available for hire, more small-scale farmers could be expected to enter wheat farming.

Currently, efforts are being made to conserve soils through the use of appropriate soil conservation practices and alternating conventional tillage with zero and/or minimum tillage. To achieve the potential yield of 4 to 5 t/ha, there have to be concerted efforts to:

- *Develop high yielding and disease resistant wheat varieties.*
- *Plant at the optimum time.*
- *Use weed control.*
- *Apply nitrogen and phosphorus fertilizer in southern Tanzania.*
- *Find reasons for the poor responses to nitrogen fertilizer in northern Tanzania where yields are still low.*

Production Trends

Over 60,000 ha of spring bread wheats are being produced in Tanzania. Durum wheat has not gained popularity yet, but it is under experimentation at several research stations.

An examination of trends of wheat production in Tanzania reveals that production continued rising from 22,000 t in 1969 to 80,000 t in 1988 (Table 1). Despite this rise in production, wheat imports have continued to fluctuate from year to year without a clear trend. For example, in 1982, total production was 95,000 t and imports were 82,000 t, whereas in 1988 production stood at 80,000 t and imports at 33,700 t (Table 1). These fluctuations have mostly been caused by the unpredictable inflow of wheat entering Tanzania under the food aid program.

In Tanzania wheat production is centered on mountain slopes and plateaus in the northern and southern highlands. All these areas receive an average seasonal rainfall of about 500 mm, the minimum required to establish a wheat crop at that altitude.

Wheat occupies fifth place among the cereals in Tanzania, but it is very important due to its role as a food for urban dwellers.

Not long after the large-scale wheat farms were nationalized in 1967, wheat production decreased from 30,332 t in 1967 to only 22,000 t in 1969. This decrease was attributed to inexperienced management of the nationalized (NAFCO) wheat farms, which shifted from wheat growing to ranching on many farms. Production increased again starting in 1978 when the large-scale, highly mechanized NAFCO farms increased production at the Hanang Wheat Complex. Today wheat produced by the NAFCO Farms in northern Tanzania accounts for 53.1% of the total national wheat production.

In the southern highlands, wheat is cultivated on about 25,000 ha of which 80% is by small-scale farmers with farm sizes ranging from 0.1 to 1.5 ha.

Yield

The average wheat yield for Tanzania is low (1.7 t/ha). Estimated yield potential is 4 to 5 t/ha. In both northern and southern Tanzania, relatively high yields approaching 2 t/ha are being achieved by the large-scale farmers. The small-scale wheat producers in the southern highlands, who commonly do not use fertilizers, obtain yields often lower than 1 t/ha because of the poorer soils existing in the area. Research is now directed toward stabilizing yields through greater attention to soil and plant health care and contingency planning to suit different weather conditions. Constraints to low yield are discussed separately.

Marketing

Most of the wheat produced in the northern highlands of the country is marketed in Arusha. The Arusha Region alone accounts for an average 98% of the wheat marketed in the country. The National Milling Corporation now procures 88% of the wheat required for milling from state farms and only 12% from private wheat farmers. In the southern highlands, more than 90% of the wheat procured by the National Milling Corporation is produced by large-scale wheat producers. Wheat produced by small-scale farmers is mostly sold in open local markets and sale

Table 1. Area, production, producer prices, and imports of wheat in Tanzania, 1969-89.

Year	Area (ha)	Producer Prices Tshs/kg	Total Production (t)	Imports (t)
1969	-	-	22,000	55,000
1970	-	-	42,850	11,600
1971	-	-	47,100	19,017
1972	-	6.45	60,000	-
1973	-	5.92	88,000	-
1974	-	5.14	85,000	-
1975	-	5.64	82,000	-
1976	-	6.34	69,000	60,200
1977	-	6.96	64,000	33,600
1978	52,000	6.48	55,000	40,500
1979	59,000	5.80	70,000	61,300
1980	55,000	5.24	87,000	32,500
1981	51,000	4.87	90,000	48,700
1982	57,000	5.24	95,000	82,000
1983	23,000	4.49	58,000	11,400
1984	59,000	4.25	74,000	46,300
1985	52,000	4.50	83,000	33,400
1986	-	4.44	72,000	21,800
1987	-	4.34	72,000	53,500
1988	65,000	23.00[a]	80,000	33,700
1989	65,000	29.00[a]	100,000	-

[a] 1988-89 producer prices are due in part to currency devaluation.

records are not easily available, but it accounts for only 1 to 5% of wheat marketed at the national level. The Tanganyika Wattle Company in Njombe is the largest commercial wheat producer accounting for 60% of marketed wheat from the south (Katunzi, pers. comm.).

Potential for Wheat Production in Tanzania

Available data from the southern highlands show that 25,000 ha of land are under wheat cultivation. There are 80,000 more in the same region suitable for wheat production. In the north, the potential is much greater than in the south with 31,000 ha under production on large-scale state farms and about 15,000 ha on small- to medium-scale private farms. Of 200,000 ha suitable for wheat production in the north, only about 45,000 ha are in production for the crop each year (Loewen-Rudgers 1988).

The land suitable for potential wheat production in northern Tanzania is fertile with no major soil problems. Therefore, if this land is fully exploited, Tanzania could produce all the wheat it requires as well as export some—even at the current yield levels.

Constraints to Wheat Production

Seed

Breeders supply seed of commercially grown varieties and advanced wheat lines to the Foundation Seed Farms. From this point on, breeders have had minimal input. The process of seed production is lengthy and during this long seed increase phase farmers must continue to use the old varieties that often succumb to diseases. Breeder involvement during the whole process of seed production through to farmer acquisition is now being introduced in an attempt to increase the efficiency of the operation.

The capacity of the Foundation Seed Farms to produce seed is limited due to the unavailability of adequate equipment for seeding, harvesting, and seed cleaning. The Tanzania Seed Company is also faced with similar problems plus the fact that its contract growers are inexperienced and often produce seed that does not quite conform to the required standard. This together with the inefficient seed distribution infrastructure stand out as major problems for the country's seed production industry.

Soil moisture

Wheat growing areas in Tanzania experience variations in moisture availability which in bad years are directly linked to differences in yield levels among various producers. However, lack of moisture is not the major yield reducing constraint. For example, studies done by McKeague and Modestus (unpublished) in northern Tanzania revealed that even an average of 350 mm of rainfall, which is well distributed, could support a good wheat crop. Usually, rainfall in the wheat growing areas of Tanzania is above this average, but it is not always well distributed (Msemwa 1979).

Problem soils

Most soils in northern Tanzania are Vertisols and Mollisols, which are fertile and without major problems and able to support a good crop without nitrogen and phosphorus fertilizers. But these soils have the general tendency to become too hard or too soft when there is drought or heavy rains, respectively, making cultivation operations difficult. They also tend to erode very easily. Soils in southern Tanzania respond to N, P, and Cu. They are highly acidic with high aluminum content and low available P. Varieties with tolerance to these problems are required in this area. Acid tolerance nurseries have been introduced and materials from them are now undergoing

evaluation (Nalitolela 1989). Copper is applied to the foliage as $CuSO_4$, Blitox, or Perenox at the 5- to 6-leaf stage of wheat growth.

Soil erosion and compaction problems

When wheat is grown as a monocrop for many years, as it is now by the large-scale producers, and especially when conventional tillage is used, weed infestation, diseases, and soil erosion become major problems. Erosion is accelerated by the lack of suitable soil conservation structures and by cattle traffic, especially at the Hanang Wheat Complex. Animal traffic can be checked by making a single cultivation after harvesting to incorporate straw which discourages cattle entry into the fields. New and suitable soil conservation structures, such as broad terraces, grass strips, and graded channels, are now being introduced at the Hanang Wheat Complex (Antapa 1989a). Minimum tillage has also been introduced to these farms to check erosion.

Soil compaction does not seem to be a problem on the wheat farms. Subsoiling trials have revealed that infiltration rates were efficient and that there were no advantages in that factor using different levels of subsoiling (Antapa 1989b).

Time of planting

Although the best wheat planting times have been established for northern and southern Tanzania, those optima are often not achieved by the large state farms. Torrential rains falling early in the season delay cultivations of Vertisol and Millisol soils in northern Tanzania. When rains subside, the few and sometimes old machines available on these farms make it impossible to complete the work rapidly. The best planting times at the Hanang and Mbulu districts are from early February to mid-March. However, a medium-maturing variety, Viri, can be planted up to early April with good yield results. In the Arumeru District and West Kilimanjaro, wheat is planted from mid-March to mid-April and during April, respectively, (W. Modestus, unpublished).

Diseases

Wheat diseases—especially leaf blotches and spots, caused by *Septoria nodorum*, Berk., *S. tritici*, Rob. and Desm. *Pyrenophora teres*, Drechsler, *Helminthosporium sativum* Ito and Kuribay, and *Fusarium culmorum* Sacc.—have become serious problems in West Kilimanjaro, the Hanang Wheat Complex, and southern Tanzania. Rusts are serious problems only in southern Tanzania.

A wheat disease survey carried out in Tanzania in 1988 revealed that some diseases such as *Puccinia graminis* f.sp. *tritici* Pers., *S. nodorum*, *P. recondita* f.sp. *tritici* Eriks. were location-specific and were confined to Hanang, Njombe, and Mbeya, respectively. Other diseases such as *H. sativum* and *Alternaria triticina* were common to all areas surveyed (Kuwite and Braun 1989).

Weeds

Large-scale state and private farms, which produce more than 90% of the wheat in Tanzania, grow wheat under monoculture. As a result, certain weed species such as *Setaria verticillata* Beuv., *Datura* spp. L., and sedges have become the dominant weeds. Control of these weeds requires at least two herbicides—one to control grass weeds and the other to control broadleaf weeds. Herbicides are expensive and yet very important in wheat production. Weed control in wheat is therefore the single most expensive production input.

Several herbicides are being recommended for use in wheat in Tanzania. For the control of grass weeds, isoproturon, metsulfuron-methyl and diclofop-methyl are used as post-emergence herbicides, and pendimethaline and trifluralin as pre-

emergence herbicides. For control of broad leaf weeds 2,4-D, MCPA, and chlorsulfuron are commonly used (Mkunga and Gillis 1990).

Price of wheat

Wheat prices are revised by the government every year and are lower for local than for imported wheat. However, at the consumer level, there are no price differentials between imported and locally produced wheat. It would therefore appear that the local, large-scale wheat producers are subsidizing imported wheat. Large-scale wheat production is highly mechanized, but since the costs of machinery, fuel, lubricants, and spare parts are more expensive in Tanzania than in the countries where the imported wheat is produced, the large-scale producers are at a disadvantage. This is one of the reasons why some farmers are stopping wheat production (B. Gillis, pers. comm.).

Diminishing Role of Small-Scale Farmers in Wheat Production

Due to the price structures, the economics of wheat growing are marginal. Unless small-scale farmers can sell their wheat at a price determined by the open market, they will not grow the crop. Wheat products sell at over 200% higher than wheat at the farm gate. Thus, a large proportion of the population cannot afford to consume wheat products and hence demand is not increasing. Although there is potential for increased production in the future, consumption will not greatly increase among the majority of low income people without a price subsidy for the finished products.

Bread Wheat Varieties Grown Commercially in Tanzania

Since 1973, 22 bread wheat varieties have been released in Tanzania for commercial production. Nine of these have already been deleted from the recommended list either because they are low yielding, do not have acceptable quality, or have succumbed to one or several fungal diseases. Many of those varieties released before 1987 such as Viri in 1983, Kozi and Joli in 1977, and Mbuni in 1975 are already susceptible to leaf spots and yellow rust. Those released in 1987 such as Mbayuwayu, Selian 87, Tausi, and Juhudi are currently being multiplied and are very popular with large-scale producers (Nbondi and Sariah 1988). However, Mbayuwayu, a high yielding variety has red kernels, which makes it less popular among small-scale producers. White-kernel bread wheats are preferred by local traders.

To date, our wheat improvement program has been able to stay ahead of any serious disease problem. Selections made from the various wheat nurseries distributed by CIMMYT have played a key role in this success.

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Resumen

Se producen más de 80,000 t de trigos harineros de primavera en unas 60,000 ha en las laderas de las montañas y las mesetas del norte y el sur de Tanzanía. La producción ha aumentado con la participación de fincas estatales en gran escala en el Complejo de Trigo de Hanang, a pesar de que varios productores en pequeña y mediana escala han dejado de producir trigo. Si se ofrecieran mejores precios para el trigo y se pudiera rentar maquinaria para la cosecha, se podría esperar que más agricultores en pequeña escala se dedicaran al cultivo del trigo.

En la actualidad se realizan actividades para conservar los suelos mediante el empleo de prácticas apropiadas de conservación y alternando la labranza tradicional con la labranza mínima y/o cero. Si se quiere alcanzar el potencial de rendimiento de 4 a 5 t/ha, se deben hacer esfuerzos concertados para:

- *Generar variedades de trigo de alto rendimiento y resistentes a las enfermedades.*
- *Sembrar en la fecha óptima.*
- *Combatir la maleza.*
- *Aplicar fertilizantes fosforados y nitrogenados en el sur de Tanzanía.*
- *Descubrir las razones de la escasa respuesta al fertilizante nitrogenado en el norte de Tanzanía, donde los rendimientos aún son bajos.*

Trends, Major Problems, and Potential of Wheat Production in Zambia

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Abstract

Wheat production in Zambia has steadily increased even though production levels still fall well short of meeting national demand. Low production can be attributed to a number of constraints including plant diseases, soil infertility, weeds, adverse climate, water and power supply shortages related to irrigation, unavailability of inputs, and lack of credit, price supports, and farmer incentives.

Despite these constraints, great potential for wheat production exists in Zambia. Much of the country has been identified as being suitable for growing the crop. High-yielding, disease-resistant varieties—for both irrigated and rainfed situations—have been released in recent years by Zambia's wheat research team. To maximize the yield potential of these varieties, recommended production packages have been developed for both small- and large-scale farmers. To support wheat production, the Government and policymakers must continue to provide incentives to wheat growers in the form of available and affordable inputs as well as reasonable market prices.

Introduction

Wheat consumption in Zambia exceeds production, forcing the country to import. About two thirds of the wheat consumed in Zambia is imported and the bulk of the remaining one third is produced locally under irrigation. Since importation of wheat is a substantial drain on the country's low foreign exchange reserves, the policy of the Government of the Republic of Zambia (GRZ) is aimed at achieving self sufficiency through increased local production.

Presently, irrigated and rainfed wheat is produced in Zambia. The bulk of this local production is from irrigated wheat, but the foreign exchange cost component involved is high (Clements 1988). Since irrigated wheat is grown in the cool, dry winter season, pressure from diseases and weeds is low. However, this production is capital intensive and hence only large-scale, mechanized farmers are involved.

On the other hand, rainfed wheat production has a low foreign exchange requirement. The crop is grown in the relatively warm, humid rainy season. Consequently, disease pressure, especially from *Helminthosporium sativum*, can be quite high resulting in serious damage to the crop. Weeds are also problematic.

In order to investigate constraints to rainfed wheat production in Zambia, a multi-disciplinary research team was assembled in 1978. Efforts of this team will, hopefully, enable farmers at all management levels of production to grow wheat. Under rainfed conditions, small-scale farmers (i.e., farmers at low-input management levels and mostly without power machinery) are the priority target group. The small-scale farming sector is estimated to account for more than 30% of national maize production. If similar levels of output can be achieved in wheat production, the country will be in a better position to meet its wheat requirements. Since Zambia shares common borders with eight countries, the opportunity for exporting wheat is also high.

Wheat Production Trends in Zambia

Although wheat is not a traditional staple food of Zambia, the increasing popularity of bread as a convenience food has led to an increasing demand for wheat over the last 3 decades. In order to meet this demand in the face of low local production, the nation resorted to importing wheat. This, in turn, caused stagnation in local production as a result of the relatively low price for imported wheat. As can be seen in Table 1, domestic production in 1975 was under 1000 t compared with 157,000 t imported during the same year. However, due to increasing scarcity of foreign currency, local production has been increasing. In 1984 domestic production accounted for 15% of the total consumption (Clements 1988) and by 1989 it accounted for about 40% of the national supply (Malisa 1989). This increase can be attributed to several factors discussed in the following sections.

Improved varieties

The introduction and development of improved and suitable varieties of both irrigated and rainfed wheat have contributed significantly to increases in local wheat production. Although rainfed wheat research and production started in the mid-1970s, more emphasis was placed on production than on research. The cultivars Jupateco 73 and Sonora 64 were used for commercial production. However, mainly due to poor resistance to *H. sativum*, yields were very low, typically ranging from 0 to 800 kg/ha (Raemaekers 1985a). Over the past few years, yields in rainfed wheat trials have risen from an average of 0.6 t/ha in the 1981-82 season to more than 3 t/ha in the 1987-88 season (Little 1989). Coucal, the latest released variety released in 1988, has a potential yield of 3.6 t/ha, out-yielding Whydah, released in 1984, by up to 40% (Clements 1988).

Similar trends have been observed for irrigated wheat. The earlier released varieties, Cojene, Jupateco 73, Limpopo, Mexipak, and Tanori, had an average yield of 4 t/ha. By 1986, with the release of Emu, Loerie, and Canary, the yield levels reached 6 t/ha (Little 1989). In 1987, Loerie II was released and achieved an average yield of over 6 t/ha. The genetic potential of the currently available irrigated varieties is in the order of 10 t/ha (Little 1989).

Improved prices for producers

The importation of commercial and food aid wheat into the country caused severe market uncertainties. Both irrigated and rainfed wheat production suffered as it was difficult for farmers to grow wheat profitably due to low producer prices. The continued devaluation of the Zambian Kwacha (ZK) worsened the problem as input costs increased while producer prices stagnated or decreased in real terms. However, due to the scarcity of foreign currency, importation of commercial wheat became more and more difficult, and at the same time, foreign countries stopped or reduced wheat aid to Zambia. As a result, the country had no alternative but to boost local production by offering higher prices, a move welcomed by farmers (Malisa 1989). The decontrol of the pricing system and the liberalization of the marketing system have made wheat production in Zambia a profitable venture and has resulted in farmers, both small- and large-scale, committing more area to wheat production. For example the area cultivated by small-scale farmers increased from none in 1986 to 600 limas (1 lima = 0.25 ha) in 1990. For the 1991 season it is estimated that 2500 limas will be planted (H. Hill, pers. comm.). Large-scale farmers, growing primarily irrigated wheat, have also increased their area from 1600 ha in 1979 (Moono and Hurd 1979) to about 8000 ha in 1990.

According to Clements (1988), the real price of wheat had increased by over 46% in 1987 over the 1979 real producer price. Production increased for the same period from 6,500 to 36,000 t with most of the increase occurring since 1984, indicating the positive response by farmers to the higher wheat prices.

Involvement of companies and large development schemes

The release of improved irrigated and rainfed wheat varieties and increases in producer prices have encouraged not only individual farmers, but also companies and large development schemes to grow more wheat. The Mpongwe Wheat Development Scheme, Plenum of Hong Kong, Masstock's Chiawa Farm, and the Gwembe Valley Development Company are some of the corporate, large-scale establishments. The contribution to wheat production by these companies will be substantial. Although irrigated wheat is the major concern of these organizations, they have recently indicated interest in rainfed wheat production (e.g., Mpongwe Wheat Development Scheme had 50 ha of rainfed wheat in 1990).

Major Wheat Production Problems in Zambia

Despite the positive trend in wheat production in Zambia, the level of production still falls short of the current national requirement (Table 1). To a large extent, this short-fall in production can be attributed to constraints discussed in the following sections.

In Zambia, rainfed wheat and irrigated wheat are grown under two different and distinct environmental situations. As a result, the two types of wheat face different biotic and abiotic constraints.

Rainfed wheat is grown during the relatively warm and humid rainy season. It is better adapted to the northern half of the country, which falls under the high rainfall agro-ecological zone. This region is characterized by high annual rainfall (1000 to 1500 mm) mostly between November and April and by cool temperatures (15 to 25°C) due to an altitude over 1400 masl (Muchindu 1985). Due to relatively high temperatures and frequent occurrence of droughty periods in

Table 1. Zambian wheat production, imports, and consumption (1975-1988).

Year	Production (t)	Imports (t)	Total Supply (t)
1975	934	157,000	157,934
1976	3,950	94,000	97,950
1977	5,324	97,000	102,324
1978	5,251	42,000	47,251
1979	6,528	106,000	112,528
1980	9,585	70,000	79,585
1981	12,479	132,000	144,479
1982	12,843	91,000	103,843
1983	10,216	64,000	74,216
1984	11,312	79,000	90,312
1985	18,000	61,000	79,000
1986	29,000	55,000	84,000
1987	36,000	21,000	57,000
1988	40,000	57,000	97,000

Adapted from Clements (1988).

the low-rainfall southern parts of the country, rainfed wheat production is considered marginally suitable for this area. In northern Zambia, rainfed wheat production is limited by crop diseases, uneven rainfall distribution, soil acidity, and low inherent soil fertility (Aulakh and Rimkus 1988).

Diseases

Due to the optimal climatic conditions during the rainy season, pathogens causing leaf spots, head blights, and seed infection are serious (Tanner and van Ginkel 1988). The most important plant pathogen is *Helminthosporium sativum* and most locations in the country are considered "hot spots" for the foliar infections and head blights the pathogen causes (Raemaekers 1985a). Although tests have indicated that effective systemic and contact fungicides for the control of the infections caused by *H. sativum* exist, their use under environments conducive to high disease pressure is uneconomic (Raemaekers 1985b). Hence, one of the major objectives of the wheat research program is to develop rainfed wheat varieties resistant to *H. sativum*. The rainfed wheat varieties released so far, through the cooperative efforts of the Zambia-Canada Wheat Project (Zam-Can) and the Belgian Development Cooperation (BDC), have considerable resistance to this pathogen.

Other diseases that are less serious, but nevertheless occur, are bacterial blight (*Xanthomonas campestris*) and scab (*Fusarium* spp.). Leaf and stem rusts (*Puccinia recondita* and *P. graminis*, respectively) are also important and have been found capable of decimating susceptible introductions. With the improvement of *H. sativum* resistance and the increase in crop area, breeding for leaf rust resistance is becoming a research priority.

The most important diseases in irrigated wheat are leaf and stem rust and powdery mildew (*Erysiphe graminis*). Resistance to these diseases is an important selection criterion in the breeding program. Older varieties, which were either less resistant (Cojene, Jupateco 73, Limpopo, Mexipak, and Tanori) or which lost their resistance (Emu'S'), are no longer recommended. The currently recommended varieties (Canary, Loerie, and Loerie II) have good resistance to these diseases. In the 1989 irrigated season, no serious disease outbreak was reported by farmers or observed by research staff (Ministry of Agriculture and Cooperatives 1989). Powdery mildew occurred sporadically and at very low levels, while stem rust did not occur. However, a new leaf rust race (*Lr26*), first reported in 1986, has now become established throughout the irrigated wheat area. This has created some concern as Loerie and Loerie II, although slow rusting, do not have resistance to this race. Canary, a susceptible variety to this new race, is no longer recommended.

Soil constraints

Irrigated wheat, mostly grown by large-scale, well established farmers, is grown on some of the best soils in the country. Hence, edaphic characteristics pose no serious constraints to irrigated wheat production.

In the high rainfall agroecological zone where rainfed wheat is better adapted, edaphic constraints pose severe limitations to wheat production. The soils in this region are highly weathered and heavily leached (Zambia-Canada Project 1984). The predominant soils in the region are Ultisols and Oxisols. Most of the soils in the region are characterized by very low levels of available plant nutrients, low pH (about 4.0, $CaCl_2$), low cation exchange capacity (CEC) of 6 to 13 me/100 g clay, low base saturation (<25%), and high aluminum saturation (>60%) in the subsoil. However, there are pockets of

soils developed from basic parent materials with relatively acceptable soil characteristics (Little 1985).

Although the poor inherent soil fertility leads to elevated costs for fertility maintenance, soil acidity is the major constraint to rainfed wheat production in the area. The soil acidity constraint may not be due to low pH per se, but due to acidity related constraints such as toxic levels of aluminum (Al) and Manganese (Mn) and critically low levels of calcium (Ca) and magnesium (Mg) (Oygard 1987).

There exists a strong negative correlation between pH and exchangeable Al (Little 1985, Msunza et al. 1983). Plants subjected to toxic levels of exchangeable Al develop stunted, thickened, and discolored root tips and lateral roots resulting in shallow rooting. This, in turn, results in ineffective utilization of soil volume and reduced uptake of nutrients and water, which limits crop growth and yields (Munyinda 1983, Little 1985, Oygard 1987). Symptoms of Mn toxicity are expressed as marginal chlorosis, induced iron deficiency, distortion of young leaves, and localized spots where Mg accumulates (Sanchez and Salinas 1981). It has been observed that Al toxicity is a more important constraint than Mn toxicity to crop growth on Zambian soils, although Mn toxicity may be expected to occur, especially on some red clay soils under anaerobic conditions (Woode 1983, cited by Oygard 1987).

In the highly weathered acidic soils, levels of exchangeable Ca and Mg are low and plants develop deficiency symptoms and poor growth. Since Mg is an important component of chlorophyll, such plants become chlorotic. Root development of plants suffering from Ca deficiency is poor. Hence, it may be difficult to isolate thought that Ca deficiency is the major cause of poor root development in highly acidic soils rather than Al per se.

While the low nutrient levels of the soils in northern Zambia could be improved by the use of fertilizers, Al and Mn toxicities and low pH require lime application. This results in high production costs which many farmers, especially small-scale ones, can not afford. In this respect, one of the major objectives of the wheat research team is to develop rainfed wheat varieties tolerant to acidity in general and Al toxicity in particular. The three varieties released so far, Whydah (ND81/IAS59// IAS58), Hornbill (IAS64/ALDAN), released in 1986, and Coucal (PF7339/ HAHN'S'), are considered tolerant to Al toxicity and low pH. Whydah (score of 3 on a 0-9 scale) is used as a check variety in selecting lines. On the susceptible side, Jupateco 73 (score of 8) is used. Performance of lines in the Al screening nurseries is scored relative to the two checks.

Summarizing results of a trial set up to study yield response to liming of three cultivars of wheat with different levels of tolerance to Al toxicity, Little (1988) lists the benefits accrued from the use of tolerant cultivars as follows:

- Allows crop production without liming in soils where production would be impossible or uneconomic without tolerance. This is particularly important when opening new land.
- Reduces the lime requirement compared with a susceptible cultivar.
- Increases production even on limed land where subsoil acidity is a factor.
- Allows a longer period of production

Weeds
Weeds are a minor production problem in irrigated wheat. Although grassy weeds are not important, broad leaf weeds could be a problem. However, these weeds are easily controlled with herbicides that are readily available in the country.

In rainfed wheat, weeds pose a major problem. This is due to intense rainfall and warm temperatures that stimulate lush weed growth. Problem weeds in the area include *Eleusine indica*, *Achyranthes aspera*, *Bidens pilosa*, *Bothriocline laxa*, *and Tagetes minuta* (Aulakh and Rimkus 1988). Results of trials conducted at Mbala show that both chemicals and handweeding can give good weed control. Since small-scale farmers have smaller wheat fields (approximately 0.25 ha each), handweeding is more practical and less costly than chemical control. Based on these results, handweeding, pendimenthalin (Stomp), diclofop-methyl (Hoegrass), 2,4-D Amine, and bromoxynil plus MCPA 1:1 (Buctril-M) are recommended weed control practices (Aulakh and Rimkus 1988). However, the use of handweeding is labor-intensive and may not be feasible at the large-scale wheat production level, leaving chemical control as the only alternative.

Other climatic factors
In addition to diseases, heavy leaching of soils, and weeds associated with high temperatures and rainfall, there are several other climatic factors limiting wheat production in tropical environments. Although variations in total annual precipitation may be small, rainfall distribution and intensity may cause problems. Intense rainfall events combined with poor infiltration may lead to severe soil erosion and occasional flooding in fields, both of which are detrimental to crop growth. It is also not uncommon to have short periods of drought. Since the water holding capacity of these soils is low, even short periods without rainfall can lead to drought stress. It has been observed that, in some years, rains may stop soon after heading, forcing the crop to survive on soil water reserves. This can result in relatively low yields due to poor grain filling and hastened maturity.

There are several physiological limitations to wheat production when grown at higher than optimum temperatures. Under such conditions, development is accelerated while growth rate is stable or may decline so that leaf size, tillering, spike size, and yield potential suffer even under irrigation. Excessive respiration and possible detrimental effects on sink formation may further reduce potential, while kernel filling is curtailed by hastened development and/or carbohydrate shortage (Fischer 1985).

Institutional constraints
As varieties are improved and better management recommendations are adopted, institutional constraints have become more of a factor in limiting wheat production in Zambia. Limited supplies of financial and technical inputs, uncertain pricing, and marketing policies for agricultural products are important constraints. Due to the governmental control prior to 1989, prices offered to the farmers were often not high enough to cover input costs. This forced farmers to cut back on input requirements resulting in yields far below potential. To control the marketing of the small quantities of wheat produced, the GRZ declared the National Milling Company (NMC) the sole buyer of wheat in the country (Clements 1988). As there are only two NMC plants (in Lusaka and Kabwe), wheat marketing became difficult and costly. This exacerbated the stagnation of the area planted to wheat. Recent price decontrol and market deregulation have led to an improvement in the country's wheat production system.

Zambia's infrastructure is poor in supporting farmer efforts to produce crops—wheat in particular. Some of the problems faced by farmers include:

- The nonavailability of cheap hydroelectric power to pump irrigation water in potentially suitable areas. The unreliable power supply results in improper irrigation schedules and consequent drought stress. Other sources of power such as diesel are extremely uneconomic.

- Scarcity of essential inputs, such as fertilizer, agricultural chemicals, and machinery, results in unnecessary delays.

- Scarcity of spare parts required for machinery maintenance. When parts are available, costs are high.

- Difficulties in obtaining foreign currency required to purchase agricultural machinery, spare parts, and chemicals.

- Difficulties in obtaining credit and the high interest involved when available. This is particularly a problem for small-scale farmers.

- Delays in delivery of inputs to marketing depots. For small-scale farmers, this means delayed operations or even cancellation of wheat production that season. For large-scale farmers, it means added costs to obtain such inputs from distant depots with adequate supplies.

- Delays in payment to farmers for their produce. This makes it particularly difficult for small-scale farmers to plan and obtain inputs for the coming season.

Potential of Wheat Production in Zambia

Despite the constraints just mentioned, the potential for wheat production in the country is high. Through the efforts of organizations such as Zam-Can, BDC, the University of Zambia (UNZA) School of Agriculture, the Horizontal Resistance Breeding Program (HRBP), and the Mpongwe Wheat Development Scheme, different wheat production recommendation packages—geared to small- or large-scale producers growing either irrigated or rainfed wheat—have been produced.

Large areas of land in Northern Province have been identified as being suitable for rainfed wheat production (Angen 1987). This is in addition to areas that are already under wheat cultivation. There is room for the expansion of the area under irrigated and rainfed wheat. The release of high yielding, well adapted varieties is encouraging farmers to plant the crop or increase the area they are already planting. In fact the rainfed variety, Coucal, has had average yields of 3 t/ha, which is 1.1 t/ha above the world wheat average (FAO 1982). The recommended irrigated wheat varieties have a genetic yield potential of 10 t/ha (Little 1989).

Coordinated efforts of research teams, extension services, financial institutions, and marketing agents are attracting increasing numbers of small-scale farmers to wheat production. Despite low levels of management, yields of 2 t/ha have been obtained. As farmers gain more experience, such yields could become normal.

Until recently, large-scale farmers were not attracted to rainfed wheat production due to the high costs per unit of wheat produced compared to irrigated wheat

(Kasalu and Johnson 1988). This was mainly due to poor yields obtained with the original rainfed wheat varieties. However, with the high yield potential of current rainfed wheat varieties, costs on a per unit basis have declined, resulting in an attitude change among commercial producers. This attitude change, however, will not necessarily be at the expense of irrigated wheat.

Institutional policies are also changing in favor of creating farmer incentives. As outlined in the Interim National Development Plan (as cited by Clements 1988) these incentives include:

- A flat tax rate of 15% on incomes derived from agriculture.
- A 2-year write-off period for farm machinery and equipment.
- An exemption of customs duty on imported agricultural machinery.
- A 50% foreign exchange retention scheme for exporters of agricultural commodities.

Recently, an incentive scheme was instituted by which a partial payment in foreign currency of US$0.50 per 90-kg bag is provided to wheat farmers who produce more than 1500 bags. Because of the foreign exchange scarcity, this income incentive makes foreign exchange available to farmers for the purchase of spare parts and essential inputs.

To help farmers remain profitable, production costs are considered when setting prices. However, the pricing policy is moving toward that based on free market systems. The gradual decontrol of producer prices and the liberalization of the marketing of agricultural products point toward such a system. Zambia's geographical position in a region with a high deficit in wheat production provides an opportunity for wheat exportation and a broadening market (Kasalu and Johnson 1988).

Following a move by the USA, Australia, and Canada to restrict wheat in the form of food aid to Zambia, a move welcomed by the country's wheat farmers (Malisa 1989), significant increases in local production have been observed.

Conclusion

Although wheat production in Zambia has been far below demand, efforts have been made to rectify the situation. As a result of efforts by Zambia's wheat research team, major biotic and abiotic constraints are no longer the most limiting factors to production. Improved irrigated and rainfed wheat varieties and appropriate cultural practices have been developed. Maintenance of existing pricing and marketing policies should ensure that Zambia's wheat area will continue to expand.

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Resumen

La producción de trigo en Zambia ha crecido continuamente pese a que los niveles de producción todavía están muy por debajo de la demanda nacional. Estos bajos niveles han sido el resultado de una serie de restricciones de carácter tanto biológico como institucional. Las restricciones biológicas incluyen las prácticas de cultivo, la fertilidad del suelo, la protección de las plantas y el manejo del agua. Las restricciones institucionales incluyen el abastecimiento de agua y energía, las facilidades de crédito, las subvenciones e incentivos para los precios y la disponibilidad de insumos.

A pesar de las restricciones, existe un enorme potencial para la producción de trigo en Zambia. Se ha determinado que gran parte del país es adecuada para el cultivo del cereal. El equipo de investigación de trigo ha lanzado en los últimos años variedades de trigo de alto rendimiento y resistentes a las enfermedades para zonas de secano e irrigadas. Con el fin de incrementar al máximo el potencial de rendimiento de estas variedades, se han formulado paquetes de recomendaciones para los agricultores en pequeña y en gran escala. Para apoyar la producción de trigo, el gobierno y quienes formulan las políticas deben continuar proporcionando incentivos a los productores de trigo mediante la disponibilidad de insumos a precios asequibles y un razonable precio de mercado.

The Wheat Development Program in Bangladesh

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Abstract

Wheat is the second most important cereal crop in the rice-based cropping systems in Bangladesh. The winter is short and mild compared to more traditional wheat-growing countries. The country produces about 1 million tons of grain from about 600,000 ha. As all available arable land is now cropped, breeding and crop management aspects have been aimed at increasing yield. The breeding program has begun to place increased emphasis on breeding for specific adaptation to the various cropping patterns and stresses. Integrated packages of practices are being developed for maximizing yield at the farmers' level. While the national yield is about 1.8 t/ha, the newly released varieties have the potential to produce more than 6 t/ha at the farm level. Management such as sub-optimal usage of fertilizers, late planting, inappropriate choice of rice varieties, and poor plant populations due to soil pests, are considered to be the most important factors responsible for the low yields.

Introduction

Bangladesh lies between 21°34' and 26°38'N latitude and 88°45' to 92°40'E longitude. Soils are broadly grouped into three categories: hill, terrace, and flood plain. Hill areas occupy about 12%, terrace 8% and flood plain about 80%. The flood area is a flat alluvial plain crossed by three large rivers and their tributaries.

Wheat area and production have increased substantially in this country since the 1972-75 period. From 125,000 ha in 1974-75, the area increased rapidly and continuously up to 591,200 ha within a period of 5 years. Simultaneously, the production increased by about 9 fold. Except for 1984-85, area and production have remained almost static since 1980-81 (Figure 1).

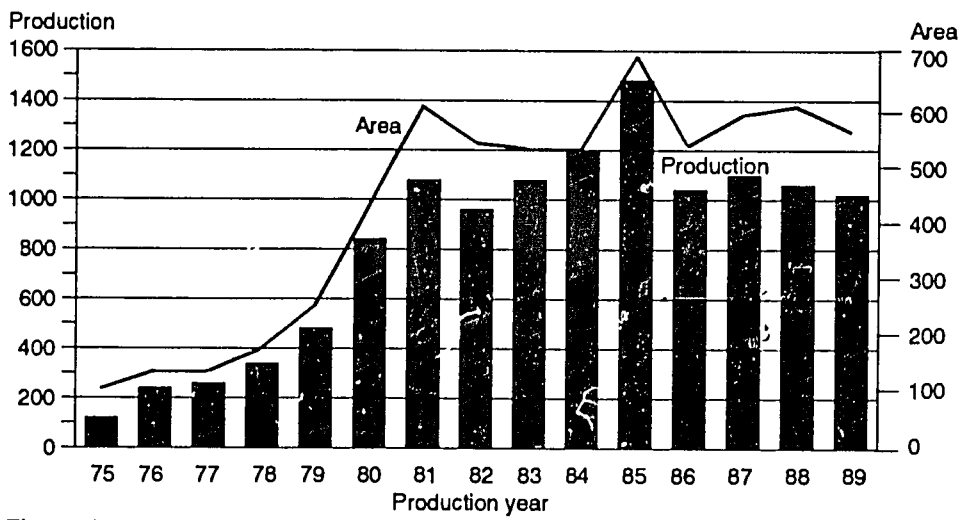

Figure 1. Trends in national wheat production (000's mt) and area (000's ha) in Bangladesh.

Climatic Considerations

The climate is dominated by tne tropical monsoon with high to fairly high rainfall. However, rainfall during the wheat crop (November to March) is low, ranging from 150 mm in the southeast of the wheat zone to 50 mm in the northwest. The mean temperature in January, the coolest month, is 18.6±1°C. Relative humidity during the wheat crop averages 70-80%.

Varietal Development Program

The breeding program has concentrated on the selection of germplasm for high yield, stable kernel weight, tolerance to heat and drought stresses, resistance to leaf rust, and improved tolerance/ resistance to leaf blotch. The crossing block is grouped into six broad categories consisting of 80 genotypes. About 350 single and 100 top crosses are made annually at several stations. Some spring x spring, and spring x winter segregating populations are also received from CIMMYT. Selections of the superior progeny from these crosses are made under both favorable and unfavorable conditions.

The pedigree method of selection was previously practiced—where only F_3 and F_4 populations are subjected to the less favorable conditions and the other generations (F_2, F_5, F_6, F_7, and F_8) to the favorable conditions. A modification was made last year for handling segregating populations on the assumption that, in the early generations, visual selection for yield potential is not very effective and performance of bulks in early generations may be a good indicator of yield. In this way, about 50% of the poor crosses can be eliminated. Moreover, spaced-planted populations are not favorable for satisfactory disease development, particularly leaf blotch. Placing emphasis on this point, F_2s are space-planted and individual plant selection is made on the basis of visual characters. F_3s are solid-seeded and the low yielding lines are discarded. The selected F_3 bulks are space-planted in subsequent generations. Here, individual plant selections are made until the lines reach homozygosity.

The segregating populations are planted at both optimum (November 15-30) and late (December 15-30) dates with irrigation at most of the locations. In one or two locations, the populations are grown at the optimum seeding date without irrigation. All selected segregating populations are maintained by the respective stations. However, one special set of F_2s is compiled from 100 g of seed from each cross from every station and grown under all environments at two stations.

The lines are cut in bulk in later generations starting from F_6 for inclusion in the Bangladesh Screening Nursery (BSN). The BSN is planted in nonreplicated 2.5-m long, two-row plots under optimum and late dates with irrigation at five locations and at the optimum seeding date in three more locations without irrigation. The selected lines from this nursery are included in replicated yield trials for optimum and late seeding dates with irrigation and optimum dates without irrigation.

Breeding Strategies

In the past, the strategy has been to develop broadly adapted varieties. More recently, the program has concentrated on the development of more specifically adapted lines.

Development of late heat tolerant varieties

Since the majority of wheat area is sown after the harvest of long-season transplanted 'aman' rice, the planting is often delayed. Late-planted crops are always subjected to high temperature

stress during the reproductive and grain filling stages, which forces the crop to prematurely ripen. High temperature at the reproductive stage hastens spike development, resulting in abortion of late-forming florets and reduction in potential kernel number (Warrington et al. 1977). The most commonly observed high temperature stress at grain filling is the acceleration of grain growth rate and reduction of grain growth period resulting in lower kernel weight (Sofield et al. 1977, Wardlaw et al. 1980, Weigand and Cuellar 1981, Bhullar and Jenner 1985). Acceleration of leaf senescence is also found (Spiertz 1974 and 1977, Al-Khatib and Paulsen 1984). Planting wheat after December 1 results in a potential yield loss of 1.3%/day per hectare for each day's delay of seeding (Saunders 1988).

In some years, late-planted crops experience excessive rainfall from anthesis to maturity (February to March) resulting in poor grain set, increased disease intensity, especially leaf spot (*Helminthosporium sativum*), as well as a higher percentage of black pointed seeds, reduced grain filling, and seed sprouting.

Figure 2 shows the performance of the most popular variety, Kanchan (UP301/C306), released to farmers in 1986. At the optimum seeding date, it is 13% higher yielding than Sonalika; at late dates, it outyields Sonalika by about 28%. Kanchan appears to have a slight vernalization response. At late seeding dates, the vegetative period is cooler, extending the time to anthesis in most varieties. However, Kanchan usually changes very little between the optimum and late dates. The total length of the growing season is reduced with late seeding due to rapidly increasing temperatures in March, thus affecting the grain-filling period. Relative to Sonalika, Kanchan is affected less (Table 1).

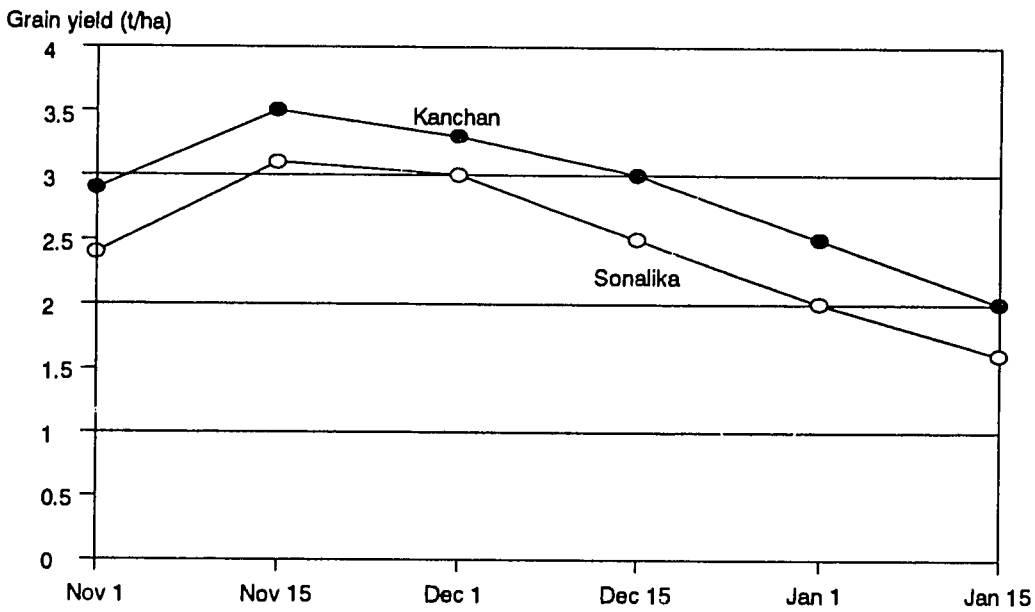

Figure 2. The effect of seeding date on wheat yields (t/ha) in Bangladesh (means of 11 experiments over 4 sites and 3 years).

Development of early heat tolerant varieties

About 10-15% of the wheat area is planted early (late October to early November) and is subjected to warm temperatures at the seedling or vegetative stage, resulting in reduced tiller number per plant, poor plant vigor, and premature heading with fewer spikelets per spike. The incidence of foot and root rot diseases is also higher under such conditions.

Selection for a longer vegetative phase with increased tillering and reduced leaf firing will minimize the yield loss. A longer duration variety of about 115 to 125 days can be accepted. The present program for the selection of early heat tolerance has been restricted to one location. This is principally winter x spring materials, planted in late October under nonirrigated conditions. Recently, high yielding, longer duration spring x spring lines have been included. Planting of these nurseries will be expanded to more locations with and without irrigation.

Development of varieties suitable for optimum planting under irrigated conditions

Varieties with high yield potential and suitable for optimum planting (from mid-November to the first week of December) are required to increase the profitability of wheat cultivation in Bangladesh. Genotypes having high yield potential are selected with a maturity range of about 100-115 days. Other selection criteria include high tillering ability, clean leaves, stiff straw, good spike fertility, and higher grain weight/spike. It is proving difficult to find lines with yields exceeding those of the currently released varieties. This has prompted an increase in the categories of parents in the crossing block (e.g., yield components). Special attributes such as semi-erect leaves and long leaf duration are being studied.

Development of varieties with moisture stress tolerance

A considerable area of wheat is planted under dryland conditions for which a maturity period of 100-110 days is desirable. Selection criteria may include high biomass with high harvest index, narrow leaves, waxiness, rapid grain filling ability, good test weight, and prolific root systems.

Development of varieties for other problem areas

Failure of grain set in some sandy soils, preharvest sprouting following continuous wet periods, and salinity in southern Bangladesh are to be addressed through development of programs targeted to these problems.

Disease and Insect Resistance

The major wheat diseases in Bangladesh are leaf rust (*Puccinia recondita*), leaf spot (*H. sativum*), foot rot, and seedling blights (*Sclerotium rolfsii*, *H. sativum*, *Alternaria tenuis*, and *Fusarium* spp.). Loose smut (*Ustilago tritici*), and head

Table 1. Changes in the duration of growth phases (days) in relation to seeding time. Wheat Research Centre, Nashipur, 1988-89.

	Kanchan		Sonalika	
	Optimum	Late	Optimum	Late
Days to Anthesis	74	74	56	67
Days of Grainfill	43	33	56	37
Days to Maturity	117	107	112	104

scab (*Fusarium* spp.) are minor diseases. Stem and stripe rusts are of no importance. Powdery mildew, septoria blotch, bacteria, and virus diseases have not yet been reported.

Leaf rust

Many resistant lines/varieties are available. Generally, a variety becomes susceptible within a period of about 6 to 7 years of release due to the changes in the virulence pattern. Leaf rust infection in the susceptible commercial varieties is observed only at the later stages of the crop (after flowering). The inoculum load is not high, perhaps due to the cultivation of resistant varieties within and outside Bangladesh. Infection at this late stage does not cause heavy damage. A study of the highly susceptible variety 'Morocco' showed a yield loss of about 53% (Ahmed and Alam 1983). Heavy artificial infection can be created by spraying inoculum in the susceptible border rows/nurseries. No study has been made to determine the prevalent rust races in the country due to the lack of facilities. About 15 high yielding, resistant lines/varieties are being utilized in the crossing program.

Leaf blotch

All commercial varieties are moderately to highly susceptible to leaf blotch (*H. sativum*). This disease is considered to be both seed and soilborne. It attacks the leaves at the seedling stage, but infection rate increases at the booting to physiological maturity stages. Recent studies indicate the yield loss is variety dependent. Incidence of this disease is higher in the old variety Sonalika—reductions in grain yield and weight were 21 and 18%, respectively, even though Tilt 250 EC at 0.125 kg ai/ha was sprayed three times in control plots. Yield losses in the new varieties Akbar, Kanchan, and Aghrani were found to be 14%, 8%, and 4%, respectively.

Incidence of this disease in the grain (black point) is also common in Bangladesh. Our experiences have shown that excessive rainfall during grain filling, particularly if the crop is lodged, causes severe infection in the grain—depending upon cultivar and location.

Breeding for *H. sativum* resistance has been initiated recently with the best available germplasm. A few lines have been identified as tolerant/moderately tolerant, the best of which is COQ'S'/F61.70//CNDR'S'/3/OLN/4/PHO'S' (CM60907-K-1Y-2M-1Y-2M-1Y-4M-2Y-0M). In this line, the top leaves are free from any infection, but some isolated lesions are found on the lower leaves.

Screening for resistance under field conditions has proven difficult. Artificial infection in the spreader rows or in the nursery by spraying inoculum or spreading infected straw at planting has not yet been successful. Space-planted segregating populations cannot create the favorable micro-environment required for proper disease development. In our opinion, the 0-9 scoring method and the two-digit system do not properly represent the infection severity. Other scoring methods, such as the percentage of dead tissue on the top few leaves, are time consuming and may not be feasible for screening large sets of materials.

Foot rot and seedling blight

Foot rot and seedling blights are caused by *S. rolfsii*, *H. sativum*, *Fusarium* spp., etc. These diseases most often occur in poorly drained soils or under drought stress.

Complete control or significant reduction of seedborne infection of the five pathogens of wheat (*Aspergillus tenuis*, *A. flavus*, *Curvularia lunata*, *H. sativum*, and *Fusarium semitectum*) has been achieved in the laboratory by seed

treatment with various fungicides (Ali and Fakir 1982b). In another study (Ali and Fakir 1982a), they found that, of 16 different seedborne fungi representing nine genera, only *A. tenuis*, *H. sativum*, and *Fusarium* spp. are pathogenic to the germinating seeds and seedlings and are partially responsible for seed rot and seedling infection.

Loose smut
Although sporadic infection in some varieties has been found, *Ustaligo tritici* has not attained any importance in Bangladesh.

Head scab
No screening for head scab (*Fusarium* spp.) has been initiated. The yield loss due to the infection of this fungus is still considered negligible.

Insects
Although no screening for resistance has yet been initiated, seedling damage caused by wireworms (the larvae of click beetles) is thought to be very important. Soilborne insects that cause seedling damage should be studied in detail and appropriate chemical controls should be recommended. Soil treatment with Furadan has significantly increased plant populations.

Stemborers, aphids, cutworms, etc. usually cause very minor damage to the wheat crop.

Varietal Demonstrations in Farmers' Fields

On-farm varietal demonstrations were initiated in 1984-85 in collaboration with the Agricultural Extension Department and the On-Farm Research Division of the Bangladesh Agricultural Research Institute (BARI) to assess the performance of new wheat varieties.

The 1988-89 results (Table 2) show data from 760 varietal demonstrations. Over all environments, the new varieties outyielded Sonalika by 17.4% (Kanchan), 12.0% (Akbar), and 9.6% (Aghrani). These demonstrations serve both as an information base for research and as a vehicle to disseminate the new varieties. In the 4 years since seed became available, Kanchan has become the predominant variety, now cultivated on approximately 50% of the wheat area.

Yield Gaps

Appropriate production technologies are needed to maximize yield. Experimental results clearly indicate that it is possible to increase the present yield level if the crop is properly managed and fertilized. For example, in 1988-89 the national average yield was 1.8 t/ha, while the mean yield of 760 on-farm demonstrations was 3.0 t/ha.

Table 2. The mean yields (kg/ha) of Sonalika and three more recently released varieties from 760 on-farm varietal demonstrations throughout Bangladesh in 1988/89.

	Moisture Regime/Seeding Date		
	Irrigated/Optimum	Irrigated/Late	Dryland/Optimum
Kanchan[a]	3609	3156	2879
Akbar[a]	3462	3016	2716
Aghrani[a]	3379	2952	2661
Sonalika	3032	2664	2511

[a] Kanchan = UP 301/C 306; Akbar = RON/TOB'S'; Aghrani = INIA/3/SON64/P4160E//SON64.

The demonstrations carried out in farmers' fields are managed by the farmers, but the Wheat Research Centre supplies fertilizer and treated seed. These inputs increased yield by more than 50% over the national average yield. From these and other special purpose on-farm demonstrations, it is possible to rank the contributing factors. Recommended fertilizer application contributes about 76% of the yield increase, seed treatment 13%, and new varieties 11%.

On-station trial check yields were about 4 t/ha, representing a further yield gap, presumably due to better seedbed preparation, irrigation, and weed control.

Factors Constraining Yield

In the last 2 years, the Wheat Research Centre has supervised Yield Maximization Demonstrations in farmers' fields. These are fairly large (0.25 ha) demonstrations of the recommended technologies—recommended levels of N-P-K-S and zinc, boron, and magnesium, depending on the location, plus 7-10 t/ha of good quality cowdung and treated seed. Yields of 4.05 to 6.25 t/ha were attained, indicating that fertility level is a major yield constraint in farmers' fields.

This has also been shown in on-station research in 1988-89. Experiments were aimed at the definition and prioritization of wheat yield constraints—fertility, soil fungi, soil insects, foliar diseases, and foliar insects. The overriding factor was soil fertility level. It is interesting to note that, even at low fertility levels (40 N:40 P_2O_5:20 K_2O—the perceived farmers' applications), there was virtually no response to farmyard manure applied at 10 t/ha.

There were significant responses in plant population to seed treatment and soil-incorporated insecticide (Furadan), but these effects were not often carried through to yield, presumably due to compensatory growth during the abnormally long, cool growing season of 1988-89.

However, at one site, the effect did cause significant yield differences. Where Vitavax-200 seed treatment or Furadan soil treatment were omitted separately from the management package, the yields were not significantly different from the full management package (4.5 t/ha). When both were omitted together, however, yield dropped to 2.7 t/ha. In some way, Vitavax can substitute for Furadan and vice-versa.

Furadan at 0.6 kg ai/ha has increased yield by 28% at the optimum seeding date and by 108% at later seeding dates. Nemacur at 1.0 kg ai/ha has increased yield by a coincidental 28% at the optimum seeding date.

The results from 87 on-farm demonstrations, comparing the yields of Kanchan and Sonalika with and without seed treatment using Vitavax-200, indicate yields up to 12.7% higher with seed treatment (Table 3).

Clearly there is a complex of soil pest problems. *S. rolfsii* is universally present and is more obvious where the plants have been drought stressed (either following drought stress then irrigated or by waterlogging). Wireworms have been observed to reduce plant populations by more than 10% per week during the seedling stage. Root-knot nematode (*Meloidogyne* spp.) galls are often observed in wheat areas with lighter-textured soils.

Over the last 7 years, many date of seeding experiments have shown that, in the southern wheat areas, the optimum seeding date is about November 15. At more northerly locations, the optimum moves toward the end of November. At

recommended input levels (potential yield 4.5-5.0 t/ha), yield reduces by 1.3% per day of seeding delay after the optimum, while at low input levels (farmers' fertilizer practice—potential yield 2.5 t/ha), the yield reduction is about 1.4% per day of seeding delay.

The losses incurred by late seeding are unaffected by seeding rate. Increased nitrogen rate also has no effect on the decline. Fertilizer efficiency is lower and the (statistical) response range is normally lower at late seeding dates (Table 4).

Many of the soils in the northern wheat zone have a pH in the range 5.2-6.5. These soils also contain relatively high levels of iron (800+ μg Fe/ml soil). It was felt that applied phosphorus might be rendered unavailable in these soils and that banding P might offer advantages. Preliminary experiments suggest that banding P increases its efficiency three-fold in comparison to broadcast-incorporated.

In the last crop season, the Wheat Research Centre distributed 200 fertilizer demonstrations of four treatments—all recommended fertilizers, P omitted, K omitted, or S omitted. It is felt that all farmers know the value of N fertilizer, but may not be convinced of the value of P, K, and S. Results are not yet available.

In 1986-87, massive head sterility was observed in the northern wheat zone, predominantly in the new variety

Table 3. The effect of seed treatment with Vitavax-200 on wheat yields in farmers' field demonstrations, 1988-89 (kg/ha, means of 87 demonstrations).

	Sonalika		Kanchan	
	Irrigated	Nonirrigated	Irrigated	Nonirrigated
Untreated	2880	2325	3300	2568
Treated	3245	2614	3666	2819
Yield Increase (%)	12.7	12.4	11.1	9.8

Table 4. The efficiency of nitrogen application (kg additional yield/kg N applied) within the responsive range, 1988-89.

Station	Seeding Date	Response Range (kg N/ha)	Response Efficiency kg yield/kg N
Jessore	Optimum	0-60	23.6
	Late	0-30	16.7
Ishurdi	Optimum	0-60	22.5
	Late	0-60	19.8
Nashipur	Optimum	0-120	17.3
	Late	0-30	16.5

Kanchan. Sonalika was largely unaffected. Farmers naturally thought that this was a varietal problem. However, soil analyses indicated that boron was below critical levels in these soils.

The incidence of sterility in the following 2 years was visually slight. However, on-farm responses to B have been consistent. From 50 on-farm demonstrations of plus/minus B in 1987-88, results were received from 29. Overall, there was a 14% yield increase with B application—Sonalika yields being more affected than those of Kanchan. In 1988-89, results from 43 demonstrations showed that Kanchan yields were increased by 12% and Sonalika by 8.5% with B application. Environmental events are most likely affecting the relative susceptibility of the two varieties.

Experiments were begun in 1988-89 to determine appropriate application technology for B. Early results indicate that, at application rates in excess of 0.75 kg B/ha, toxicity occurs. Even at rates of up to 4.0 kg B/ha, there is no residual activity in the year after application in the light-textured soils of the northern wheat zone.

Sustainability of the Rice-Wheat Systems

Over the past few years, there has been some concern over an apparent decline in yield of wheat in the rice-wheat system. The yield reduction could be due to changes in climate as suggested by some. Others suggest that wheat is being pushed into progressively more marginal areas by increased irrigation facilities becoming available in some areas that are taken over by winter rice.

While both of the above factors may contribute to a yield decline, there is a stronger line of thought suggesting that increased cropping intensity accompanied by minimal inputs and virtually zero return of crop residues are leading to an erosion of nutrient resources. Certainly, over the years, responses have become progressively evident to P, K, S, and Zn. More recently, it has been found that B, Mg, and Mo may be reaching critical levels.

If nutrition is reaching critical levels, the crop is then under stress and, as a result, the plants become less tolerant of diseases and, consequently, the relative yield loss to (often weak) pathogens becomes greater. The solution to this yield decline problem or the stimulation of on-farm yields requires an integrated approach involving agronomy, soil science/plant nutrition, and plant pathology.

During the last crop cycle, a farmer survey was carried out involving 200 farmers in the Greater Dinajpur area in the extreme northwest. The area is characterized by very sandy soils. The farmers are among the most resource-poor in the country. There have been reports of yield declines in the various rice-wheat cropping systems of this area particularly. While there is a popular misconception that little organic matter is returned to fields, the survey showed that farmers apply an average of nearly 6.0 t/ha of farmyard manure.

For wheat grown under dryland conditions, the survey showed an average application of inorganic fertilizer of 47 kg N, 49 kg P_2O_5, and 26 kg K_2O/ha for an average yield of 2 t/ha. Under irrigated conditions, average fertilizer applications were 72 kg N, 55 kg P_2O_5, and 25 kg K_2O/ha for an average yield of 2.75 t/ha.

When asked whether yields were increasing, static, or decreasing over the long-term, 20% of farmers said rice yields were decreasing and 15% thought wheat yields had declined as well (Table 5).

There was little difference between the total sample of farmers and those who had been rotating wheat and rice for 10 years or more. The most affected cropping pattern was the wheat-aus rice rotation. Aus rice is generally the crop that receives the lowest fertilizer inputs. Farmers felt that declines were due to decreased soil fertility, but they were financially unable to apply more fertilizer.

Conclusions

By continued crossing and selection, there is potential for increasing resistance to foliar diseases and to lodging in Bangladesh. Yield improvement is proving more elusive and requires changes in methodology.

Crop management research must be strengthened in respect to soil, fertility, and water management and must be based on a cropping system approach.

Regional and international cooperation will be required to continue the adaptation of wheat to the nontraditional warmer areas.

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Table 5. Long-term yield changes in the rice-wheat rotation as perceived by farmers in a 1990 survey in northwestern Bangladesh.

Rice-wheat rotation	Percent of farmers in each cropping rotation					
	Rice yield			Wheat yield		
	Increase	Stable	Decrease	Increase	Stable	Decrease
Aman-wheat	49	34	17	41	44	15
Aman-wheat -aus	44	40	16	40	44	16
Wheat-aus	38	19	43	57	33	10
All farmers	46	34	20	43	42	15
Long-term farmers[a]	42	37	21	43	38	19

[a] Farmers who have been practicing a rice-wheat rotation for 10 years or more.

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Resumen

Por su importancia, el trigo ocupa el segundo lugar en los sistemas de cultivo de Bangladesh, basados en el arroz. El invierno es breve y benigno en ese país, en comparación con los países donde el trigo es un cultivo más tradicional. Bangladesh produce alrededor de 1 millón de toneladas de grano en unas 600,000 hectáreas. Como toda la tierra arable ya es explotada en la actualidad, el mejoramiento y el manejo de los cultivos se han orientado a aumentar el rendimiento por unidad de superficie. El programa de mejoramiento ha comenzado a hacer más hincapié en la adaptación específica a las diversas modalidades de cultivo y a los factores desfavorables. En el presente se están ideando conjuntos integrados de prácticas para aumentar al máximo el rendimiento a nivel de las fincas. Si bien el rendimiento nacional es de unas 1.8 t/ha, las variedades lanzadas recientemente tienen el potencial para producir más de 6 t/ha a nivel de las fincas. Se considera que prácticas de manejo tales como la utilización subóptima de los fertilizantes, la siembra tardía, la elección inapropiada de las variedades de arroz y la escasa densidad de las poblaciones como resultado de las plagas del suelo, constituyen los factores más importantes que contribuyen a los bajos rendimientos.

Potential for Wheat Production in Indonesia

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Abstract

The high rainfall and hot, humid environments in Indonesia are not considered favorable for wheat production. The domestic demand for wheat, however, remains high. It is met entirely by imports and requires substantial foreign exchange. Recent advances in technologies for wheat production in humid tropical environments have prompted Indonesia to initiate research to develop technologies for domestic production of wheat. Several varietal trials have indicated that, under appropriate soil and climatic conditions, wheat can be produced economically. An evaluation of climatic conditions indicates that temperatures that will allow wheat to grow occur in the Indonesian highlands 350 meters above sea level (masl) and above. Multilocation trials indicate a linear increase in wheat yield with increasing elevation, if there is no damage from pests and diseases and if appropriate planting times are chosen. Surveys indicate a potential land area of 31 million hectares where wheat production may be possible. Soil acidity and infertility, however, present a serious challenge. Fertile, nonacid soils occur at elevations of 700 to 1000 masl, but these areas are exclusively devoted to high value vegetable and fruit crops. Wheat will, therefore, have to be developed for lower elevations where soil management technologies will need to address the problems of soil acidity and infertility. A comparison of rainfall patterns and duration of dry seasons indicates that the eastern part of Indonesia may present a better environment for wheat production.

Several trials have been carried out at Sukarami Agricultural Research Institute for Food Crops. These trials have identified wheat cultivars having acceptable yield potential and desirable grain quality. Additional trials have been conducted to determine appropriate planting times and disease control methods. Average fertilizer requirements have been established. Work has begun to screen varieties or cultivars for high temperature, high rainfall, and acid soil conditions.

Introduction

With a total production of 25.8 million tons of milled rice in 1984, Indonesia, for the first time, became self-sufficient in rice production, after having been known as the world's largest rice importer for many years. However, Indonesia continues to be challenged by high population growth, adverse weather, pest and disease infestations, and loss of fertile lands to industrial development (buildings, roads) and more profitable crops. It is estimated that nearly 30,000 ha of fertile land in Java are lost to such purposes every year (Affandi 1986).

Indonesia imports a large amount of wheat and other grains each year. In 1989, wheat imports amounted to more than 2 million tons. The entire national demand for wheat is met by importing it from other countries, at huge costs.

To reduce the large drain of already limited foreign exchange and to increase self-reliance, the Central Research Institute for Food Crops has, for the last decade, carried out a varietal improvement program to develop wheat varieties.

Wheat is actually not a new crop in Indonesia. There is evidence that it was cultivated several centuries ago, especially in relatively isolated highlands such as Pangalengan in West Java, Dieng Plateau and Salatiga in Central Java, and Bromo-Tosari in East Java (Danakusuma 1985).

Wheat, being relatively drought tolerant, is a potential alternative crop where cool and dry months occur. The development of adapted wheat varieties will contribute to crop diversification.

Since production areas in other countries have expanded towards the equator in recent years, much attention has been given by scientists to develop wheat varieties suitable for tropical climates. Curtis (1988) divided the tropical countries into two types of environments:

- High temperatures, dry, short crop seasons, with few disease problems.
- High temperatures, more humid, short crop seasons, and having significant disease problems.

While Indonesia is classified into the second type of environment, both types of environments can be found in Indonesia, with the eastern part of Indonesia representing the first type and the western part having the second type of environment.

At present, the Sukarami Research Institute for Food Crops (SARIF) has the national mandate to conduct research for the development of wheat in Indonesia. Research is focussed on the evaluation of germplasm for specific disease and stress problems. In addition, soil management practices, fertility management, weed control, and integrated methods of disease control are being researched.

Target Areas for Wheat Production

Wheat grows under relatively cooler temperature regimes and requires fertile soils. Therefore, attention needs to be given to identification of suitable lands and elevations where wheat yields are least depressed. If wheat is to replace an existing crop, it must be more profitable than the replaced crop. Wheat may be promoted as an additional crop in rotation with other crops (Balittan Sukarami 1990).

Climate and soil factors

Air temperature and soils are both important factors when considering wheat as a potential crop for Indonesia. The optimal temperature for wheat growth is 10 to 20°C (Fischer 1983). While such temperatures do occur at latitudes 20° and higher, their occurrence near the equator is largely dependent on elevation. The Indonesian islands lie within a few degrees of the equator. The climate is generally hot and humid. Cooler temperatures, however, do occur at higher elevations. Figure 1 presents a graph of the variations in minimum and maximum temperatures as a function of elevation. These data show that temperatures in the range of 10 to 20°C do not occur in Indonesia. Recent studies in Philippines (Aggarwal et al. 1987), however, show that wheat can grow in the humid tropics where temperatures range from around 21 to above 30°C, commonly occurring in Indonesia at elevations of 300 meters above sea level (masl) (see Figure 1). Therefore, it is possible for wheat to grow in Indonesia.

A distinct dry or drier season is a characteristic of the weather patterns for both eastern and western Indonesia. In East Indonesia, however, the dry season is much drier and longer. This may be an important consideration in choosing areas

for wheat production. High rainfall and humidity may promote weeds, disease, pests and weeds, and interfere with harvesting operations.

In addition to elevation, soil acidity, aluminum toxicity, and low fertility are critical factors. Except for the island of Java, soil properties seem to vary with elevations. More fertile soils of volcanic origin (Andosols or Andepts) almost always occur on higher elevations (Subagjo 1988). Lower elevations are occupied by highly acid and low fertility Oxisols and Ultisols and to some extent relatively fertile Inceptisols/Entisols. Oxisols and Ultisols occupy large areas on the islands outside Java (Table 1). These soils show aluminum saturations of from 60 to 90%. They are very low in organic matter content and exchangeable bases. Losses of nitrogen and P-fixation greatly aggravate fertility problems. Subagjo (1988) showed that soils at elevations of 350 masl and lower are basically all Oxisols and Ultisols, while Andosols occur at elevations of 700 masl or above. A progression of aluminum and base saturation of soils with elevation is shown in Figure 2. Although Inceptisols and Entisols are relatively more fertile, they occur in the recent flood plains (around 50 masl or lower), where waterlogging and higher temperatures may cause serious limitations.

Restrictions due to temperature limit the choice of lands for wheat production to elevations above 350 masl. However, all lands that are available are not cultivable. Uncultivable areas include lands on hilly terrain (above 1500 masl) and those with

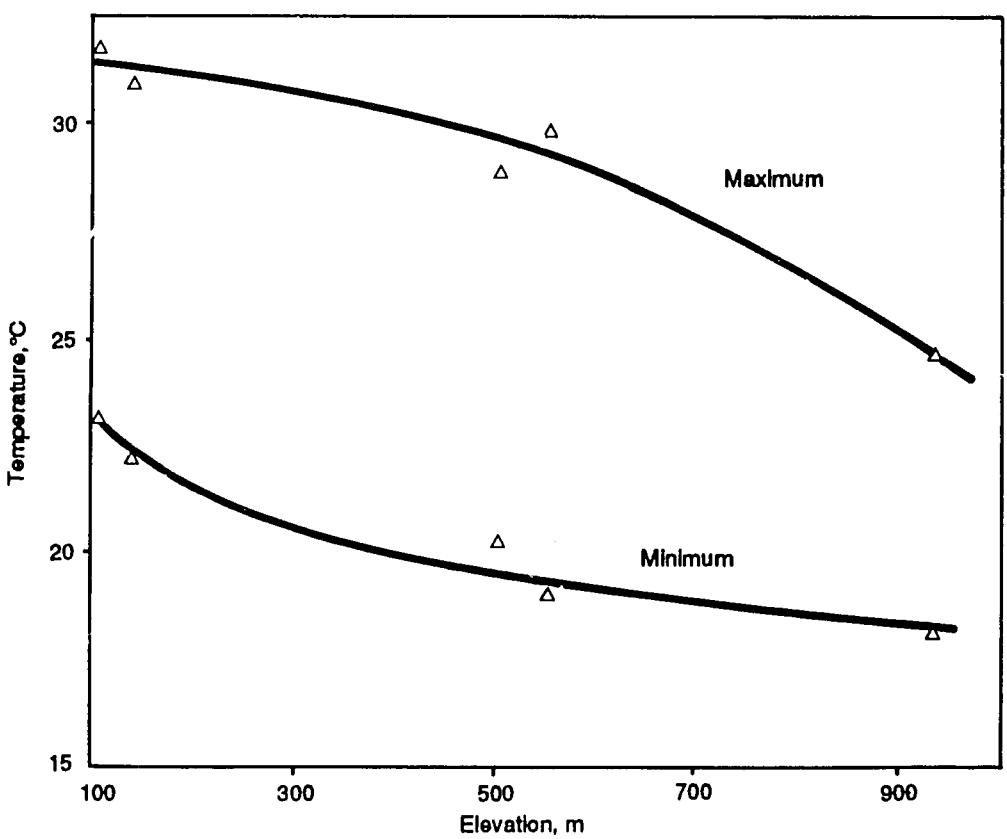

Figure 1. Variation in air temperature with elevation.

Table 1. Distribution of land with acid problems on seven islands of Indonesia.

Islands	Alluvial[a] (Inceptisol-Entisol)	Latosol (Oxisol)	Organosol (Histosol)	Podzol	Podzolic (Ultisol)	Complex[a]
			'000 ha			
Java Madura	2,550	2,775	25	-	325	1,919
Sumatra	5,682	6,018	8,875	1,031	14,695	7,962
Kalimantan	5,744	4,468	6,523	4,581	10,997	20,438
Sulawesi	1,562	2,649	240	-	1,308	10,129
Bali/Nusa Tenggara	312	563	-	-		2,388
Maluku	488	331	525	-	2,406	2,670
Irian Jaya	2,575	356	10,875	-	8,706	18,607

[a] Includes nonacid soils.
Source: Soil Research Institute (1981).

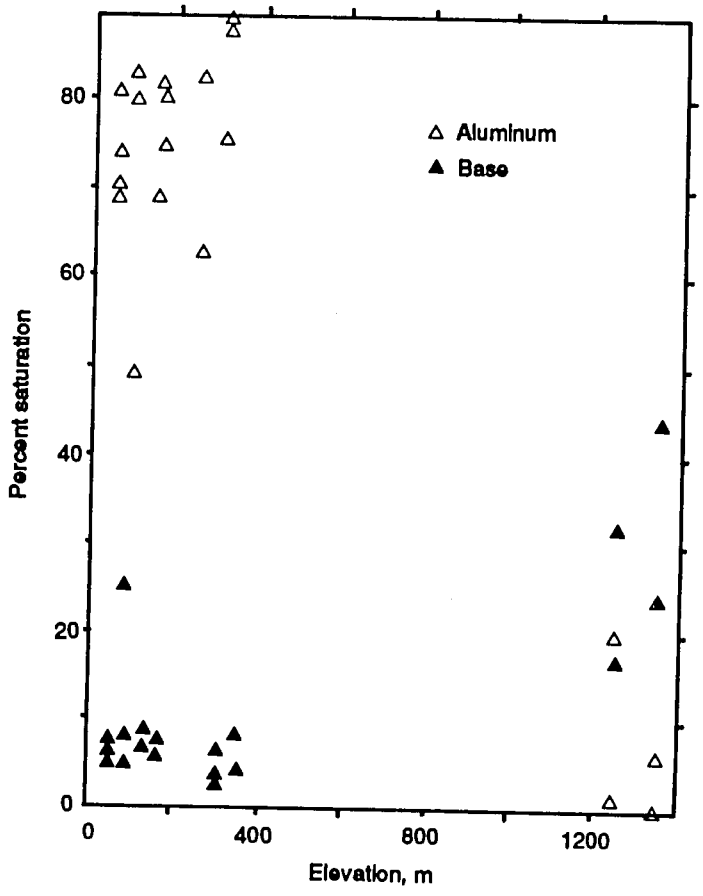

Figure 2. Changes in aluminum and base saturation with elevation.

slopes in excess of 15%. Table 2 presents the land area with slopes considered suitable for cultivation. Based on these data, cultivable Latosols (Oxisols) and Podzolic soils (Ultisols) present a potential area of about 31 million hectares. But this figure also includes areas that are situated at elevations lower than 350 masl. An estimate of the potential cultivable area and area at elevations higher than 350 masl is currently unavailable. Andosols and transitional areas between Oxisols and Andosols are probably better suited for wheat, both from the view of temperature regime as well as soil acidity/fertility aspects. But wheat would have to compete with vegetable and fruit crops at higher elevations and, considering the socioeconomics of farming communities at higher elevations, it seems that wheat will not be able to compete with those high-value crops. Wheat in rotation with other crops may, however, be possible.

Thus, potential lands for wheat production in Indonesia lie from the transition between Andosols and Oxisols, about 1700 masl, to about 350 masl. However, soil acidity and fertility will remain important soil management issues.

Research Highlights

Wheat, an important food crop, has not yet been successfully grown in Indonesia. Wheat supply for domestic consumption comes entirely from external sources. This makes Indonesia vulnerable not only to changes in price, but also to changes in the supply of wheat in the world market. An interest in developing wheat as a domestic crop in Indonesia is, therefore, natural.

Results of studies on wheat genotypic adaptation to Indonesian agroecological environments show that wheat can grow and produce fairly well. Wheat in Indonesia is still at the research stage with commercial production yet to come. The following reviews wheat research through 1989 in Indonesia.

Varietal improvement

The long-term objectives of the wheat improvement program in Indonesia are to develop wheat cultivars suitable for the country's tropical conditions. The program places special emphasis on the identification and development of superior germplasm with tolerance to abiotic stress such as drought, acid soil, high rainfall,

Table 2. Estimates of land areas with acid problems and slopes less than 15%.

Islands	Alluvial[a] (Inceptisol-Entisol)	Latosol (Oxisol)	Organosol (Histosol)	Podzol (Ultisol)	Podzolic (Ultisol)	Total
			(millions of hectares)			
Sumatra	2.4	0.5	8.9	0.8	9.6	22.2
Kalimantan	4.3	-	6.5	2.5	10.9	24.2
Sulawesi	0.8	-	-	-	1.4	2.2
Irian Jaya	2.6	-	6.7	-	5.1	14.4
Total	10.1	0.5	22.1	3.3	27.0	63.0

[a] Includes nonacidic soils.
Source: Danakusuma (1985).

and high temperature and biotic stress such as diseases caused by *Fusarium* spp. and *Sclerotium rolfsii*.

Most of the materials were received from CIMMYT/Mexico in the form of advanced lines. The results of the evaluation of advanced lines follow.

Cultivar adaptability—Azwar (1984) conducted an experiment to determine the effect of elevation on growth and yield of wheat in the tropical environment of Indonesia. Results of this experiment and those from other experiments show that growth is linear with elevation, if there is no damage from pests and diseases (Table 3). Wheat yield increased as the elevation increased. However, factors such as planting time and disease infection can influence the yield potential at any given location.

At low elevations (less than 300 masl), high temperatures caused the plants to develop poorly and they failed to produce grains. At medium elevations (350-600 masl), yields from several locations, both in eastern and western parts of Indonesia, averaged 1.5 t/ha, with up to 2.8 t/ha at Kuningan in West Java (where experience with wheat is extensive and, hence, management is good). Yield potential at high elevations (above 600 masl) is location specific. The highest yield obtained at Tlekung (1300 masl), an average of the seven best lines, was 3.5 t/ha. Results indicate that, at Tlekung, the

Table 3. Effect of elevation on wheat yields (t/ha) of selected cultivars in Indonesia.

Location	Elevation (masl)	Cultivars							Average
		Trigo 1	SA 75	Lyallpur 73	Lok 1	Punjab 81	V 1287	IWP 72	
Mojosari[a] E. Java	30	0.62	0.59	0.84	0.59	0.32	0.34	0.52	0.55
Jambegede[a] E. Java	335	2.05	1.38	1.31	1.83	2.36	2.04	1.68	1.81
Kendalpayak[a] E. Java	435	1.10	1.30	1.50	0.99	-	1.09	0.95	1.17
Rambatan[c] W. Sumatra	500	0.87	1.16	1.08	1.09	1.04	1.00	1.07	1.04
Kuningan[b] W. Java	550	2.76	2.08	2.14	3.00	2.69	3.08	2.71	2.78
Talang[c] W. Sumatra	660	1.65	1.01	1.65	1.70	1.96	1.30	1.47	1.53
Sukarami[c] W. Sumatra	920	1.53	1.41	1.46	1.73	1.72	1.84	1.80	1.64
Bukittinggi[c] W. Sumatra	1000	1.52	1.82	1.41	2.78	2.16	2.12	1.18	1.86
Lemgang[b] W. Java	1100	1.83	2.84	1.11	3.21	3.84	2.90	2.40	2.59
Tlekung[b] E. Java	1300	-	3.57	4.32	2.38	-	3.58	3.21	3.51

[a] Kusmana and Subandi (1985).
[b] Balittan Sukamandi (1985).
[c] Balittan Sukarami (1990).

environment was very close to the requirements of wheat in terms of temperature and rainfall patterns. Yield differences between Tlekung (eastern part of Indonesia) and Sukarami and Kerinci (located at almost the same elevation) were closely related to differences in rainfall patterns, amount of radiation, and relative humidity. Low yields at Kerinci and Sukarami were due to high relative humidity and high rainfall which caused high incidence of scab disease (*Fusarium* spp.). In general, the cultivar Lok 1 performed well in the west and Lyallpur 73 appeared better adapted in the east.

Milling quality—In general, wheat cultivars that have performed better under Indonesian conditions also produce good grain quality. The average flour yield and protein content of six cultivars were 59 and 12%, respectively, and baking quality of the flour was also good, especially SA 75 which had a 62% flour yield, high protein content, and strong gluten quality (suitable for making bread).

Higher rainfall areas—One hundred and ten advanced lines designated for higher rainfall areas were tested at Sukarami during May to August 1989. Most of the lines produced low yields, ranging from 0.7 to 1.1 t/ha.

Acid soil environments—During 1989, 108 and 49 lines of the 7th and 8th Bread Wheat Acid Soil Nurseries, respectively, and 69 lines of 5th Barley Yellow Dwarf Virus Nursery were evaluated under acid soil conditions in Talang, West Sumatra. Yields ranged between 0.8 and 1.6 t/ha.

Warmer areas—The 2nd and 3rd Warmer Area Wheat Screening Nurseries (WAWSN) were tested in Rambatan, West Sumatra, in 1989. Because of lack of rainfall during the growing times (only 154 mm) the plants failed to grow normally.

Resistance to fusarium head scab—Scab is the most serious disease on wheat, especially in areas with high rainfall and humidity. Tnis pathogen can lead to the total failure of the wheat crop. Apparently, warm humid areas are more favorable for the disease and is especially serious in China, southern Brazil, Argentina, and western Europe (Zillinski 1983).

During 1989, 71 wheat F_2 populations were planted and selected lines from these populations were continued to the F_3 generation. During 1990, 163 lines from the 1st Fusarium Head Scab Screening Nursery were planted in Sukarami where scab is one of the major problems for wheat production. The trial is still in the field and hopefully, some lines with increased scab resistance will be identified.

Cultural practices

Row spacing and cultivars—This study was aimed at determining the optimum row spacing for five wheat cultivars. With a seed rate of 100 kg/ha, closer row spacings (20 cm) had lower populations within the row than wider row spacings. It is suspected that lower populations within the row allows more light penetration, resulting in increased number of spikes/m^2 and grains/spike. This must have had an effect on the grain yield. The results are shown in Table 4.

Time of planting—To determine the effect of time of planting on yield and yield components of wheat, a trial was conducted at Sukarami with one cultivar (Table 5). Planting dates were from January to December. Maximum grain yields were obtained for planting dates from March to June. Earlier plantings experienced partial waterlogging during the initial stages of growth. Later plantings were exposed to progressively increasing rainfall, higher relative humidity, and lower radiation,

particularly after anthesis. The higher rainfall and relative humidity and low radiation after anthesis resulted in scab and grain yields were reduced. This trial demonstrated that grain yields above 1.5 t/ha can be obtained in Sukarami if the planting date is from Febrary through June.

NPK fertilizers—NPK fertilizer trials were conducted at four locations (Rambatan, Talang, Alahan Panjang, and Kerinci) to determine their optimum rates for wheat. All P and K and two thirds of N fertilizers were applied at planting time and the remaining N was applied 1 month later. The best combination was 90-45-60 NPK kg/ha (Table 6) although the response efficiency of all applications was low.

Disease control—Five fungicides were tested for scab control. Two fungicides, propiconazole and thiophanate methyl using rates of 0.4-0.5 L/ha and 0.77-1.12 kg/ha, respectively, were found effective (Table 7). The fungicides were applied at 1-week intervals, beginning at anthesis.

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Table 4. Effect of row spacing on yield and yield components of wheat cultivars at Sukarami (means of five cultivars).

Row spacing (cm)	Grain yield (t/ha)	Spikes/ m^2	Grains/ spike	1000 grain wt. (g)
20	3.0	363	29.9	39.1
30	2.9	313	33.3	38.4
40	2.3	291	31.6	37.7

Table 5. Effects of planting date on the yield and yield components of a wheat cultivar at Sukarami.

Planting Time	Seeds/ spike	100 seed weight (g)	Yield (t/ha)
January	26.5	22.7	0.9
February	33.3	32.6	1.8
March	31.5	36.1	1.4
April	35.8	34.3	1.0
May	36.3	40.0	1.7
June	31.3	35.8	1.7
July	37.3	25.4	0.8
August	43.3	26.1	0.8
September	36.1	26.6	0.6
October	0.0	0.0	0.0
November	0.0	0.0	0.0
December	25.5	22.1	1.1

Source: LP3 Sumbar (1978).

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Table 6. Effect of different levels of NPK fertilizers on wheat yield (t/ha) during 1987 at different locations in Sumatra.

NPK	Rambatan	Talang	Alahan Panjang	Kerinci	Average
90-45-0	0.74	2.04	1.74	1.77	1.57
90-45-60	0.80	2.11	1.92	2.58	1.85
90-45-120	0.91	2.76	1.67	2.40	1.94
0-45-60	0.18	1.37	1.76	1.82	1.28
30-45-60	0.44	1.80	1.84	1.30	1.35
60-45-60	0.50	1.61	1.82	2.36	1.57
120-45-60	0.56	2.49	1.92	1.36	1.58

Table 7. The influence of different fungicides and rates on scab infection in wheat and subsequent yield.

Fungicides and rates	Scab damage (%)	Yield (t/ha)
Propiconazole (Tilt 250 EC)		
0.40 L/ha	32.97	1.24
0.50 L/ha	32.78	1.55
Thiophanate methyl (Topsin M 70 WP)		
0.77 kg/ha	35.87	1.65
1.22 kg/ha	32.69	1.26
Without fungicide	92.30	0.89

Source: Balittan Sukarami (1990).

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Resumen

En Indonesia, los ambientes húmedos y muy cálidos, con precipitaciones elevadas, no se consideran favorables para la producción de trigo. Sin embargo, la demanda interna de trigo sigue siendo alta y se satisface totalmente mediante importaciones que requieren una cantidad considerable de divisas. Los avances recientes en las tecnologías de la producción de trigo en ambientes tropicales húmedos han estimulado a Indonesia a iniciar investigaciones con el fin de generar tecnologías para la producción interna de trigo. Varios ensayos de variedades han indicado que, en condiciones climáticas y del suelo apropiadas, se puede producir el trigo en forma económica. Una evaluación de las condiciones climáticas revela que las temperaturas que permiten el desarrollo del trigo se producen en las tierras altas de Indonesia situadas a 350 metros sobre el nivel del mar y a mayor altitud. Los ensayos en localidades múltiples muestran un incremento lineal en el rendimiento del trigo al aumentar la altitud, cuando no existe daño provocado por plagas y enfermedades y se escogen fechas apropiadas de siembra. Las encuestas indican que existe una superficie potencial de 31 millones de hectáreas donde tal vez sea posible producir trigo. No obstante, la acidez y la esterilidad del suelo plantean un serio desafío. Los suelos no ácidos fértiles se encuentran a una altitud de 700 a 1,000 m sobre el nivel del mar, pero esas tierras están dedicadas exclusivamente al cultivo de hortalizas y frutas de alto valor. En consecuencia, habrá que generar variedades de trigo para altitudes más bajas, donde las tecnologías de manejo del suelo tendrán que abordar los problemas de la acidez y la esterilidad. La comparación de los patrones de la precipitación pluvial y la duración de las estaciones secas revela que la parte oriental de Indonesia puede constituir un ambiente mejor para la producción de trigo.

Se han efectuado varios ensayos en el Instituto Sukarami de Investigaciones Agrícolas sobre Cultivos Alimentarios. En esos ensayos se han identificado variedades de trigo con un aceptable potencial de rendimiento y conveniente calidad de grano. Se han realizado ensayos adicionales para determinar las fechas de siembra apropiadas y los métodos de lucha contra las enfermedades. También se han establecido los requerimientos medios de fertilizante. Se ha iniciado la labor de selección de variedades para condiciones de altas temperaturas, precipitación elevada y suelos ácidos.

Wheat Research Efforts in Vietnam

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Abstract

The Vietnam Agricultural Science Institute (VASI) has conducted research on wheat and barley since 1968. Although the early effort to commercialize wheat in Vietnam during the 1971-73 period failed due to a lack of suitable varieties, three target environments for production were identified: 1) rainfed in the northern mountains at high elevation, 2) rainfed in the northwestern mountains, and 3) irrigated in the Red River Delta. The most important breeding objectives include earliness and resistance to diseases such as spot blotch, powdery mildew, leaf rust, and fusarium head scab. New introductions from various origins are listed that outyield the old local checks and combine all necessary traits. In the Red River Valley, close crop rotations dictate that wheat be sown before early November, the optimum date. Foggy weather occurs at flowering, resulting in poor grain filling, sprouting, and grain drying problems. Currently, a complete lack of milling facilities in the north prohibits rapid commercialization of wheat.

Introduction

Vietnam is a tropical country in Southeast Asia lying between 9 and 23°N latitudes. It has a population of about 64 million (1989) and a total area of 329,556 km^2. Rice is the staple food. Food production in 1989 was approximately 21 million tons, but this production is not stable. In some years, storms and floods inundate the Red River Plains of northern Vietnam, and large rice areas suffer total losses (e.g., 200,000 to 300,000 ha in 1985). Products from wheat such as bread, cakes, biscuits, and noodles are common in the Vietnamese diet. Annual wheat flour imports are 100,000 to 300,000 t.

To decrease food deficiencies and wheat imports, wheat has been considered as a winter crop in northern Vietnam, which has average temperatures of 23°C in October and 18 to 20°C in November through March. The coolest month is January with an average of 16°C. Rainfall is low—only 100 mm in the November-March period. During February and March, relative humidity is high (85 to 90%).

Production

In Cao Bang Province in the northern mountains, rainfed wheat has been grown for many centuries from October to April at mid-elevations (200-300 masl), using local varieties with low (less than 1 t/ha), but stable yields. Mean temperature of the coolest month, January, is 14.0°C. In the Son La and Lai Chau Provinces in the northeastern mountains, at higher elevations (700 masl) with increased solar radiation, but a slightly higher January mean temperature (16.0°C), wheat has also been grown successfully. In the South, rainfed wheat can be grown three times a year at high elevations, such as Duc Trong (1020 masl) in Lam Dong Province. Due to competition from other crops, this area may not be suitable for commercial production. However, it is extremely useful for rapid seed multiplication of promising lines and advancing of segregating generations as well as for screening for tolerance to heavy rain, spot blotch, and fusarium head scab during the summer, when wheat can not be grown in the North.

The largest potential wheat environment is the Red River Plains of northern Vietnam. There, the variety Thanh Uyen has been grown in the past in small church gardens to produce wheat flour for religious purposes. During 1971-1972, 200 t of Sonalika and Kalyansona were introduced to Vietnam to rapidly increase the area planted to wheat. In 1971, 1200 ha of wheat were grown in all provinces of North Vietnam with an average yield of 1.2 t/ha and top yields of 3 to 4 t/ha. In 1972, the wheat area was 800 ha and the average yield was 0.8 t/ha. By 1973, these varieties and wheat in general had disappeared completely due to lack of suitable varieties for these climatic conditions (Table 1).

Research

The Vietnam Agricultural Science Institute (INSA) has studied wheat and barley since 1968. Although commercial wheat production failed, wheat research has continued since that time on a limited scale.

Breeding

Breeding objectives are:

- Earliness.
- Spot blotch resistance.
- Powdery mildew resistance.
- Leaf rust resistance.
- Fusarium head scab resistance.
- Acceptable yield potential of 2 to 3 t/ha.

The total number of cultivars introduced by INSA from CIMMYT and ICARDA during 1977-1990 were: 3305 bread wheats, 402 durum wheats, 950 triticales, and 1115 barleys (Table 2). Table 3 lists advanced lines that are high yielding, early, and moderately resistant to the relevant diseases.

Diseases

The important diseases are:

- Spot blotch (*Helminthosporium sativum*).
- Leaf rust (*Puccinia recondita*).
- Powdery mildew (*Erysiphe graminis*).
- Head scab (*Fusarium graminearum*).

These four diseases occur in all parts of northern Vietnam and usually develop in February and March. In some warm and/or humid years, epidemics may start in

Table 1. Climatic parameters for the wheat growing season in the Red River Plains (Hanoi).

Month	Temperature (°C) Average maximum	Average minimum	Rainfall (mm)	Relative humidity (%)	Hours of sunshine
October	28.8	21.6	123	85	186
November	25.6	18.2	47	81	148
December	22.0	15.0	20	81	121
January	20.4	13.8	18	80	85
February	20.4	14.7	26	84	54
March	23.1	17.5	48	88	47

Latitude: 21°01'N; Longitude: 105°48'E; Altitude: 5 masl.

December or January. The reactions of advanced lines to these diseases on the Red River Plains are shown in Table 3.

Leaf rust and powdery mildew have not been found in southern Vietnam (Duc Trong, Lam Dong) during 6 years of experiments. Bacterial blight and barley yellow dwarf virus (BYDV) were found, but were not serious.

Crop management

Optimum sowing dates, spike density, and fertilizer rates have also been studied. The optimum sowing time for wheat is early November. This results in high yields of 3 to 4 t/ha, but there are also many problems during harvesting that occur in February and March when high humidity (85 to 90%) causes difficulties with threshing, sprouting, and grain drying. This harvest date also conflicts with the transplanting of spring rice, which usually begins on February 5. Therefore, the most convenient sowing time may be early October using early varieties, which can escape diseases and sprouting, yield 2 to 3 t/ha, and be harvested before transplanting of spring rice.

The average number of spikes/m^2 ranges from 250 to 300, but 400 to 500 spikes/m^2 were also obtained in experiments (Table 4).

Weeds

Weeds are a problem in rainfed summer sowings (from May-October) at Duc Trong in southern Vietnam. In the main production areas of the North, weeds are controlled manually and pose no problem in the intensely cropped fields.

Common weed species of wheat in Vietnam are *Cyperus rotundus*, *Eleusine indica*, *Digitaria* spp., *Cynodon dactylon*, and *Amaranthus* spp.

Insects

Aphids and green bugs are considered important during December to March. Grasshoppers are important pests on

Table 2. Amount of germplasm introduced by the Vietnam Agricultural Science Institute (INSA) from 1977 to 1990.

Year	Bread wheat	Durum wheat	Triticale	Barley
1977-78	347	-	-	-
1978-79	675	-	-	-
1979-80	530	-	328	25
1980-81	431	-	285	50
1981-82	-	-	-	239
1982-83	96	-	-	236
1983-84	-	-	-	-
1984-85	207	306	207	150
1985-86	-	-	-	-
1986-87	-	-	-	-
1987-88	464	-	-	-
1988-89	405	-	-	-
1989-90[a]	450	96	130	315

[a] Introductions from ICARDA; introductions in all other years from CIMMYT.

Table 3. Yield potential and disease readings of advanced lines for the Red River Plains.

Line or cross	Origin	Yield (kg/ha)	Days to heading	*H. sativum*	Leaf rust	Powdery mildew	Head scab
Cao Bang (local check for rainfed mountains)	Vietnam	1050	100	5	50S	5	MR
Thanh Uyen (local check)	Vietnam	2584	65	3	100S	9	MS
Line 11	Vietnam	3230	65	5	100S	5	MR
Sonalika	India	1777	50	7	50S	7	S
BH1146	Brazil	1932	52	5	30S	5	MR
Trigo 3	Philippines	2235	55	5	50S	7	na
Kea'S' CM21335-C-9Y-3M-1Y-1Y-0B	CIMMYT	2356	48	5	50MR	7	MS
Chat'S' CM33090-N-1M-1Y-0M-59Y-0B-1Ptz-0Y	CIMMYT	4733	71	5	na	5	na
Bow'S' CM33203-K-9M-9Y-4M-1M-1Y-0M	CIMMYT	4466	50	5	20MR	5	MR
CRT/ALD'S' CM37214-0M-6L-2L-1L-0L	CIMMYT	2350	47	3	TMR	5	na
MAD'S'/BJY'S' CM49640-3M-2Y-2Y-2M-0Y	CIMMYT	2066	50	5	TMR	3	MS
BUC'S'/BJY'S' CM49641-6M-1Y-3Y-2M-0Y	CIMMYT	3000	50	5	na	3	na
ALD'S'/PVN'S' CM49901-14Y-2Y-6M-4Y-2M-0Y	CIMMYT	3581	73	3	20MR	5	MR
IAS58/4/KAL/BB//CJ/3/ALD'S' CM50464-12Y-2F-2Y-1Y-3M-1Y-0M	CIMMYT	2540	50	5	30MR	3	VS
TUC'S'/MON'S'//VEE'S' CM62001	CIMMYT	2954	65	3	20MR	3	R
BOW'S'//YD'S'/ZZ'S' CM62045	CIMMYT	na	na	5	10R	3	S
F3.71/TRM SWM4275-41M-1Y-4M-1Y-0m	CIMMYT	na	na	5	10R	3	S

Rating scales:
Helminthosporium sativum and powdery mildew: 0 to 9 (0 = no visible disease, 9 = susceptible) taken 85 days after sowing.

Leaf rust and scab: MR = moderately resistant, R = resistant, t = traces, MS = moderately susceptible, s = susceptible, VS = very susceptible; percentages of leaf rust according to modified Cobb scale.

wheat seedlings of October-sown crops. Mole crickets, army worms, and cutworms have been found feeding on wheat. Wireworms and white grubs are only important in the South. Rats and birds threaten wheat seriously every year.

Commercialization

The potential wheat area in the lowlands of northern Vietnam is estimated to be about 600,000 ha and in the mountainous provinces of northern Vietnam about 140,000 ha. An attempt to revive wheat production was made in 1987. Thanh Uyen and Line 11 were grown in five provinces (Cao Bang, Lai Chau, Son La, Hanoi, Ha Nam Ninh) totaling 70 ha. Average yields of 1.0 t/ha and top yield of 2.2 t/ha were obtained. In 1988, the wheat area decreased to 40 ha with an average yield of 0.8 t/ha. In 1989, only Cao Bang Province had 20 ha of wheat. The development of a commercial wheat crop has been restricted by a number of factors: lack of suitable machinery for seedbed preparation, threshing and drying; unattractive prices; and the lack of marketing channels and milling facilities in the proposed production areas.

Table 4. Yield components of several introduced varieties under Red River Plains conditions.

Varieties	Spikes /m²	Grains /spike	1000 grain wt.
Sonalika	430	21.9	42.0
Kalyansona	387	29.2	29.2
INIA 66	446	24.8	32.2
UP 301	488	18.3	27.0
CIANO 79	514	20.3	37.0
Kea'S'	372	25.4	33.5

In 1989, the national wheat program was reorganized with the following objectives:

- Increase wheat areas.
- Investigate the problems in wheat production.

Acknowledgments

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Resumen

El Instituto de Ciencias Agrícolas de Vietnam (VASI) ha realizado estudios sobre trigo y cebada desde 1968. Aunque los primeros intentos de comercializar el trigo en Vietnam en 1971-1973 fracasaron por la falta de variedades adecuadas, se identificaron tres ambientes de producción: (1) las tierras de secano a gran altitud en las montañas septentrionales, (2) las tierras de secano en las montañas del noroeste y (3) las tierras irrigadas en el delta del río Rojo. Los objetivos más importantes del fitomejoramiento incluyen la madurez temprana y la resistencia a enfermedades tales como la mancha foliar, el mildiú polvoriento, la roya foliar y fusariosis de la espiga. Se enumeran las variedades nuevas de diversos orígenes que se han introducido y que superan el rendimiento de los antiguos testigos locales y combinan todas las características necesarias. En el valle del río Rojo, la rotación de los cultivos obliga a sembrar el trigo antes de comienzos de noviembre, la fecha óptima. La niebla que se produce durante la floración da como resultado el llenado deficiente de los granos, la germinación prematura y problemas en el secado del grano. En la actualidad, la ausencia total de instalaciones de molienda en el norte impide la comercialización rápida del trigo.

Trends, Major Problems, and Potential of Wheat Production in Brazil

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Abstract

Important changes in Brazilian wheat production, consumption, and policy have occurred in the last 5 years. Annual production during the 1985-89 period was 5.5 million tons (Mt) compared to 2.2 Mt during the 1980-84 period. Average national yield increased from 998 kg/ha during 1980-84 to 1634 kg/ha in 1985-89. During the 1985-89 period, wheat area increased 30%. Wheat consumption decreased from a peak of 57 kg per capita in 1980 to 46 kg in 1989. These trends were due to the Government's policy of using domestic wheat production to substitute for wheat imports whenever possible, the Government's monopoly of buying and selling all domestic and imported wheat, and farmers' adoption of new technologies.

With the new Brazilian government, a recent policy change toward market integration with other countries in South America has come about. Brazil has agreed to import up to 2.2 Mt of wheat annually from Argentina over the next 5 years.

Wheat production was stimulated in the 1980s by a farmer price that was 33% above the imported wheat price at the official exchange rate. However, this value decreases to 12.5% if the shadow exchange rate is used, which eliminates the over-valuation of the Brazilian currency. The new Government policy of allowing the exchange rate to fluctuate freely and a completely liberalized trade policy will influence future wheat consumption and production.

Wheat production in the traditionally cultivated areas could expand to an additional 1.6 million hectares on existing agricultural land without competing with other crops. Average wheat yields could reach 2.5 t/ha. Even if per capita consumption grows to a projected 55 kg and the population increases to 180 million by the turn of the century, realization of potential production would ensure Brazil's self-sufficiency in wheat.

Introduction

The increase in Brazil's wheat production has been outstanding—considering the great environmental difficulties that the crop must endure. About 75% of Brazil is tropical and 25% is humid with a warm spring season that favors plant diseases. Its soils, in general, have low fertility and acidity problems extend across large areas. Even so, wheat production in Brazil has increased rapidly until today more than 2 million tons (Mt) are annually produced in the southern states and 3.5 Mt near and above the Tropic of Capricorn—mostly in the state of Paraná—a new region of production (Hettel 1989).

To understand and evaluate the major trends, problems, and the potential of wheat production in Brazil, one must know what has been accomplished, how it was done, and the present situation—with emphasis on the decade of the 1980s.

Present Situation

Production, consumption, and prices

In 1989 about 5.6 Mt were produced on an area of 3.3 million hectares—hence an average yield 1.7 t/ha. Brazilians consumed 6.7 Mt (46 kg per capita) made up of the 5.6 Mt of domestic production (84%) and 1.1 Mt of imported wheat (16%) (Ministerio da Agricultura 1990).

Farmers were paid, on average, US$165.70/t, while imported wheat cost was US$155.98/t (FOB). The cost at the mills was, on average, US$187.20/t for locally produced wheat and US$202.80/t for imported wheat.

The Federal Government, through the Bank of Brazil, was the only buyer for both domestic and imported wheat, which was sold to mills at a fixed price with quotas for each mill. The Government also fixed the prices of wheat products. The carryover at the end of 1989 was 5.6 Mt or 84% of the wheat consumption.

For the above 1989 figures to be truly meaningful, it is necessary to know what happened in the 1980s as a whole. During the decade, there were important modifications that will help identify trends and the potential of wheat production in the short-term.

Table 1 shows the evolution of Brazil's wheat production. Yields and production have stabilized since 1985. In the 1985-89 period, production increased by 152% due to a 30% increase in wheat area and a 64% increase in yield over the 1980-84 period. As a consequence, Brazilian farmers' contribution to total Brazilian wheat consumption increased from 30.4% in 1980-84 to 64.2% in 1985-89 and in the last 2 years was 82.5% (Table 2) (Ministerio da Agricultura 1990).

Table 1. Evolution of wheat production and yield in Brazil.

Years	Production (1000 t)	Yield (kg/ha)
1962-64	182	675
1970-72	1488	747
1980	2707	865
1981	2209	1151
1982	1827	646
1983	2236	1190
1984	1983	1139
1985	4320	1614
1986	5870	1472
1987	6034	1746
1988	5751	1652
1989	5595	1687

Source: Fundação Instituto Brasileiro de Geografia e Estatistica. Anuario Estatistico do Brasil (Rio de Janeiro: FIBGE, various years) and Ministerio da Agricultura (1990).

The prices paid to the farmers were higher in 1980-84 (US$226.29) than in 1985-89 (US$ 204.27); the 1989 price was the lowest of the decade (Table 3). At the mill during 1980-89, domestic wheat, on average, was more expensive than imported wheat by US$55.50 or 29.6%. This difference at the beginning of the decade was low, increased to a maximum in 1985, and then decreased until 1989 when the price of domestic wheat dropped below that of imported wheat.

Per capita consumption before subsidization was as low as 36.4 kg in 1970 (Table 4). Per capita consumption during 1980-84 was 50.16 kg, but decreased during 1985-89 to 46.72 kg.

Production regions

There are currently two major wheat regions in Brazil:

- The south—the States of Rio Grande do Sul, Santa Catarina, and southern Paraná. Here frosts occur every year with an intensity that does not allow the growth of cold-sensitive crops during the winter.

- The north—northern Paraná and the states of São Paulo and Mato Grosso do Sul. Here frosts are less frequent (or do not occur) and temperatures during the winter are higher than in the south. The wheat cultivation area is located 4° below the Tropic of Capricorn and 3° above it (Figure 1).

An area with great potential for wheat production includes the states of Minas Gerais, Goias, Mato Grosso, and Bahia.

For many years, the southern states were considered the only suitable area for production—and most research devoted to developing wheat for Brazil was limited to this region. Later in the 1970s, the subtropical region further to the north was recognized as a possible wheat area and was subsequently developed, particularly after the influx of soybean production. Today, the northern region produces 60% of Brazil's wheat (Table 5).

Major Constraints to Wheat Production

Southern region

Soils—Acidity with aluminum toxicity, low fertility (mainly phosphorus), and

Table 2. Domestic and imported wheat milled during the 1980-89 period.

Year	National (000 t)	(%)	Imported (000 t)	(%)	Total
1980	2084	31	4718	69	6802
1981	2180	36	3896	64	6076
1982	1666	27	4440	73	6106
1983	1872	30	4447	70	6319
1984	1764	28	4612	72	6376
1985	1794	30	4339	70	6133
1986	4696	65	2507	35	7203
1987	4071	61	2626	39	6697
1988	5171	81	1233	19	6404
1989	5741	84	1123	16	8864

Source: Ministerio da Agricultura (1990).

Table 3. Prices (US$/t) paid to the farmers, price of imported wheat (FOB), and the prices of national and imported wheat at mills during the 1980-89 period.

Year	Price to farmers	Imported (FOB)	Price at mills National[a] A	Price at mills Imported[b] B	Difference in price at mills A - B
1980	190.00	173.65	214.70	225.70	- 11.00
1981	236.43	185.26	267.20	240.80	+ 26.40
1982	275.00	168.97	310.70	219.70	+ 91.00
1983	204.01	161.02	230.50	209.30	+ 21.20
1984	225.90	150.00	255.30	195.00	+ 60.30
1985	248.31	144.86	280.60	188.30	+ 92.30
1986	241.33	109.60	272.70	142.50	+130.20
1987	184.79	90.65	208.80	117.80	+ 91.00
1988	181.23	103.70	204.80	134.80	+ 70.00
1989	165.70	155.98	187.20	202.80	- 15.60
Average	215.28	144.37	243.20	187.70	+ 55.50

[a] Price paid to farmers, plus 13%.
[b] FOB price, plus 30%.
Source: Ministerio da Agricultura (1990).

erosion and compaction caused by heavy agricultural equipment are the major soil problems. Liming has essentially solved the aluminum toxicity problem in the topsoil, but there is still aluminum toxicity in the subsoil that affects root growth. Aluminum-tolerant varieties identified in the early breeding programs partially solved the problem until adequate liming was done. Today, aluminum tolerance is a necessary trait if roots are to grow into the subsoil. Only recently have cultivars been coming out of the breeding pipeline with a combination of Al tolerance, short straw, and high yield potential. Previously, the only Al-tolerant cultivars were tall genotypes and these still predominate in the region.

Soil infertility has been ameliorated with application of high rates of phosphorus and lower quantities of nitrogen and potassium. Today, many soils have an adequate supply of phosphorus and so farmers are applying increasing amounts of potassium. The nitrogen requirement has, in part, been supplied by the previous soybean crop.

Initially, the large amounts of lime applied to soybeans had harmful effects on wheat production, in that the lime favored diseases such as take-all (*Gaeumannomyces graminis* var. *tritici*) and Soilborne Wheat Mosaic Virus (SBWMV).

Climate—High relative humidity during the growing season, mainly in the spring, favors diseases. Frequent rains during this time make it difficult for efficient disease control through spraying of contact chemicals. Efficient systemic fungicides have helped to solve this problem and their use is one of the important factors responsible for stabilizing wheat production.

Late frosts have been a problem because early cultivars are used to fit the soybean-wheat rotation pattern. Recent revisions in sowing dates for the whole rotational system have helped to minimize frost damage. Rains at harvest time, in some years, decrease wheat quality and test weights.

Diseases—For many years, common root rot (*Helminthosporium sativum*) and take-all were ignored, which resulted in low yields and unstable production. Crop rotation can contribute to efficient root disease control. The cultivation of oats, rape, flax, and legumes during the winter

Table 4. Per capita consumption (kg) of wheat in Brazil.

Year	Consumption
1970	36.4
1980	57.1
1981	48.9
1982	48.1
1983	48.7
1984	48.0
1985	45.2
1986	52.0
1987	47.0
1988	43.4
1989	46.0

Source: Bank of Brazil-CTRIN.

Table 5. Distribution of wheat production, by region as a percentage of total production.

Years	Southern	Northern
1967-69	93.9	6.1
1972-74	72.6	27.4
1977-79	51.1	48.9
1982-84	46.1	53.9
1987-89	39.8	60.2

for a period of 1 to 3 years and soybeans or fallow in the summer and autumn helps break the disease cycle by lowering inoculum of the root disease pathogens to levels that do not affect yields during winter seasons when wheat is grown (Santos et al. 1987).

The main leaf and ear diseases are *Septoria tritici* and *S. nodorum*, *Helminthosporium* spp., leaf and stem rusts (*Puccinia tritici* and *P. graminis*), scab (*Fusarium* spp.), and loose smut (*Ustilago tritici*).

Although breeding has been successful in developing tolerance or resistance to some of these diseases, fungicides are still required to ensure high yields. Seed treatment helps to control leaf and spike diseases. Recommended chemicals include: thiram, iprodione, and triadimenol—alone or combined with benomyl, carboxin, and captan; iprodione-thiram, or triadimenol-iprodione. Benomyl, carboxin, and triadimenol control loose smut (Reunião da Comissão Sul-Brasileira de Pesquisa de Trigo 1990).

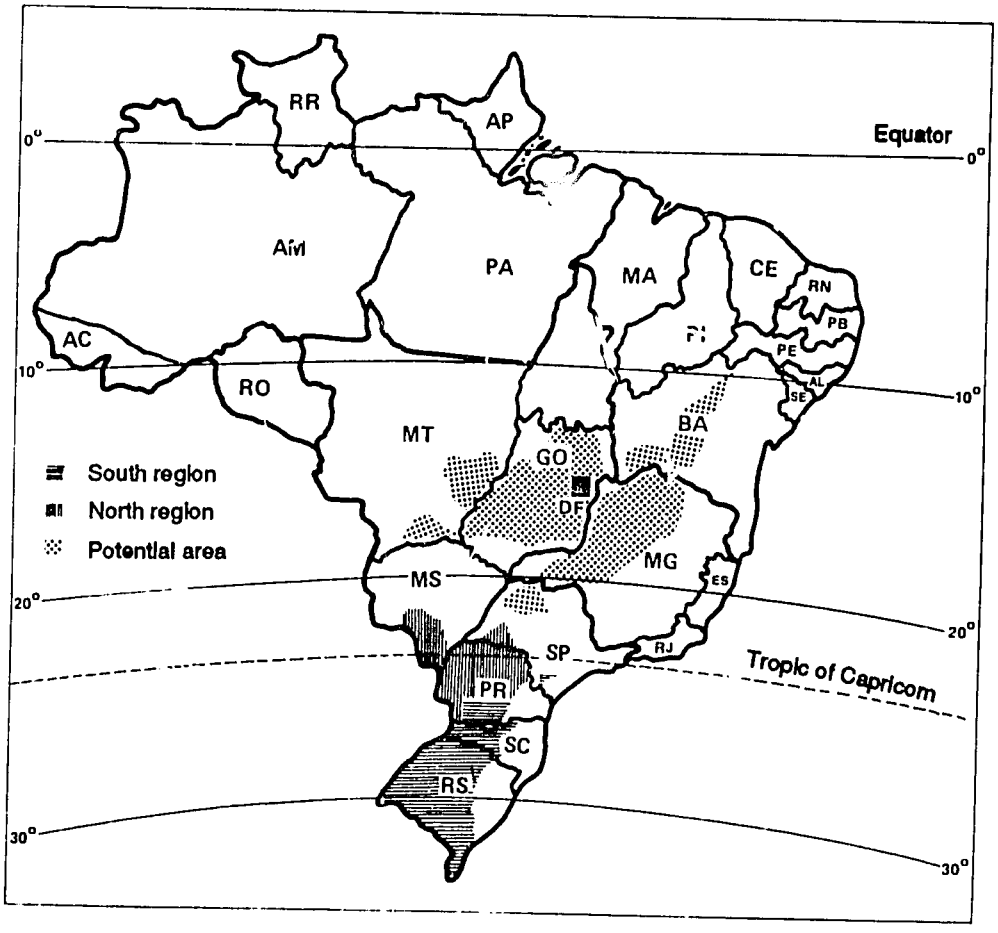

Figure 1. Current and potential wheat growing areas of Brazil.

Fungicides that farmers use for leaf diseases include propiconazole, triadimenol, and maneb + triadimefon; for scab, they use benomyl, carbendazin, thiabendazole, and methylic thiophanate. Use of systemic fungicides has increased and has helped to stabilize yields even under climatic conditions favorable to the diseases.

Pests—Aphids, previously important, have been effectively controlled by the successful introduction of natural parasites, which today eliminates the need for large quantities of insecticides previously considered essential.

Soil degradation—Because of the intensive two-crop system and seedbed preparation with excessive use of disk harrows, topsoil structure has been degraded and the subsoil compacted. This has resulted in erosion, reduction of soil water holding capacity, and restriction of root growth to the upper soil layer.

These problems have been minimized by the use of the straw as a surface mulch, tined cultivators, and crop rotation. Soil cover during the winter season protects against erosion; a green manure crop is recommended when wheat is not planted. More farmers are using zero tillage, which guarantees soil conservation if the soil has already been improved and is in good condition.

Crop adaptation to local conditions—Extensive studies of the climate and soils and many variety trials have led to the zonation of the southern states for wheat production. Rio Grande do Sul has eight zones, Santa Catarina has five, and southern Paraná has two—where specific recommendations are made to the farmers regarding cultivars, sowing dates, and other management practices (Reunião da Comissão Sul-Brasileira de Pesquisa de Trigo 1990).

Northern region

Soils—Soils in the north, in general, have better inherent fertility than in the south. There are large areas where there is no aluminum toxicity, so the cultivation of Mexican cultivars is successful. There are areas where aluminum toxicity occurs, mainly in soils originally covered by grasses (campos) or by savannas (cerrados) predominant in Mato Grosso do Sul. Most of these soils have low fertility; phosphorus and some potash and nitrogen are required, depending on the organic matter content.

In part of this region, there were once great erosion problems, which not only limited wheat yields, but also discouraged production of other crops. The solution has become a model for many other regions and has been recognized as such by many international organizations, including the Food and Agriculture Organization (FAO). The main points were recognizing the need for soil conservation and that its attainment was a community responsibility. As a consequence, planning commenced and water and runoff controls were instituted.

Soil compaction problems have been solved by methods similar to those in the south. Farmers are beginning to adopt zero tillage, but as in the south it is still a limited practice.

Climate—The climate is dryer with lower relative humidity and occasional droughts that affect yields, but in many regions drought effects are reduced by the high water holding capacity of the soil and the plants' deep root systems.

Frosts in the north can reduce yields in some years. Because of the sowing time, they occur when the wheat is at the reproductive stage. To avoid this problem, careful zoning was established for recommended sowing dates.

Diseases—Root rots and leaf diseases (except the rusts) are less severe than in the south. Rice blast (now called wheat blast by some) is a new disease in wheat caused by *Pyricularia oryzae*. Its effect can be reduced by early sowing, planting less susceptible cultivars, and the use of mancozeb fungicides (OCEPAR 1990). See Igarashi's poster on wheat blast in these proceedings on page 480.

Bacteriosis occurs in the north and is difficult to control; the use of seed from areas free of this disease is recommended.

Weeds—There are weed problems as elsewhere, but in the soybean-wheat system they are easier to control because of the alternation of broadleaf and cereal crops.

New potential area for wheat

There is a very large potential area for wheat production between latitudes 8° to 21°S in some river basins, such as São Francisco; at low altitudes; and on the plateaus above 400 masl in the central part of the country. The major problems in these areas have to be divided into those of rainfed and irrigated crops (Reunião da Comissão Centro-Brasileira de Pesquisa de Trigo 1988).

Rainfed crop—Rainfed wheat is limited to the high plateaus above 800 masl between 13°30' and 21°S. The wheat crop, under these conditions, uses only half or less of the rainy season since there are no crops that can be economically produced during the first part of the rainy season from November to January. Although beans, peanuts, early rice, and early soybeans can be planted during this period, their harvest would be in the middle of the rainy season, which dictates the need for crop drying—in addition to a disease risk. Early rice and soybean cultivars yield less than the late cultivars of these crops.

On the technical side, dry periods during the rainy season may cause unstable wheat yields and increase the infestation of the insect *Elasmopalpus lignosellus*, which is a limiting factor during dry spells.

The soils are poor and acidic with aluminum toxicity, but they are easily improved by lime and fertilizer applications. Soybeans are grown extensively under these conditions. The topography is flat or gently undulating, which facilitates mechanized soybean production. There are no drainage problems and soil conditions are adequate for utilization of sprinkler irrigation systems.

Wheat yields are comparable to the southern and northern regions in areas that have cool summers, such as the high plateaus in Minas Gerais.

Irrigated crop—The main obstacle with irrigated wheat during the dry season (May to September) is competition from other crops, mainly field beans and dry peas. Although it is not difficult to harvest 4 t/ha of wheat (some farmers have obtained 5.5 t/ha), it is more profitable to produce 1.5 t/ha of beans or 2.5 t/ha of dry peas.

A major constraint to wheat production was male sterility, which caused yield instability—sometimes lowering it to 200 kg/ha. Boron deficiency was identified as the cause with variable effects due to interactions with hot spells (above 28°C) and low relative humidities (below 40%). Application of 1 kg B/ha, which has a residual effect of at least 3 years, has effectively solved the sterility problem (da Silva and de Andrade 1979, 1983).

Disease problems, under irrigation, are stem rust and leaf rusts, mildew, virus diseases, and possibly nematodes. Under the climatic conditions of the dry season

(very low relative humidity), no important incidence of helminthosporium, the septorias, or gibberella has been reported. Even in soils that have been in wheat production for more than 10 years, helminthosporium root rot has not become an important constraint (da Silva et al. 1976).

Wheat Production Potential in Brazil

Production increases through area expansion

Total rainfed wheat area expansion of about 400,000 ha in the southern states is possible—250,000 ha in Rio Grande do Sul, 125,000 ha in southern Paraná, and 25,000 ha in Santa Catarina. In the north, 1.2 million hectares of wheat expansion is possible—400,000 ha in northern Paraná, 30,000 ha in São Paulo, and 770,000 in Mato Grosso do Sul.

These potential areas are estimated based on the area currently cropped to soybeans. In the south, because of wheat root rots, it is only possible to plant one third of the soybean area to wheat. In Paraná, all the soybean area is included. In Mato Grosso do Sul, it is estimated that all the cultivated area in the southern part of the state may be possible for wheat cultivation. In São Paulo, the Paranapanema Valley and parts of the south are suitable for rainfed wheat (Table 6).

The expansion of the wheat crop in the areas mentioned is possible without interfering in the production of other crops because wheat is cultivated during the winter when no other major crop can be raised. In the state of Mato Grosso do Sul, it is possible to open new areas for agriculture in the cerrados and grasslands—and part of these areas may be used for wheat production.

Where irrigation is available, the possible expansion area is very large and a low estimate is 1 million hectares. Presently, the area irrigated by sprinklers is 350,000 ha and most of that can be planted to wheat during the dry season. The main crops currently irrigated by center pivot sprinkler systems are beans and dry peas, but their market is limited and their high price is due to exceptional conditions of the market. When beans are planted after soybeans, there is a tendency for soilborne diseases to become a limiting factor—making a rotation with crops of the grass family desirable, which would make growing wheat or maize for seed a viable option.

Table 6. Wheat and soybean areas in Brazil during the 1985-88 period ('000 ha).

	Wheat					Soybeans				
	1985	1986	1987	1988	average	1935	1986	1987	1988	average
Rio Grande do Sul	971	1169	998	1012	1037	3637	3243	3157	3436	3368
Santa Catarina	40	116	125	100	95	420	382	362	386	387
Paraná	1302	1947	1717	1775	1685	2196	1745	1718	2115	1943
São Paulo	155	213	180	194	187	498	475	462	512	486
Mato Grosso do Sul	201	396	425	344	341	1308	1206	1151	1176	1210

Source: Fundação Instituto Brasileiro de Geografia e Estatistica—Anuario Estatistico do Brasil (Rio de Janeiro: FIBGE, various years) and Ministerio da Agricultura (1990).

The sprinkler irrigated area, mainly with center pivots, has increased substantially in the last 5 years. Brazilian factories can currently produce enough irrigation equipment for annual additions of 100,000 ha of land under irrigation.

There is also the possibility of irrigating wheat through surface irrigation, particularly in large areas of the São Francisco River Basin. Many settlements in this region are being divided into small farms, which are not suitable for large-scale mechanized grain production.

Expansion of production through yield increases

The national average yield of 1.65 t/ha could be raised to more than 2 t/ha within a short time if farmers adopted available technology. During the last 3 years, both large- and small-scale farmers growing rainfed wheat in the north and south have realized yields of 3 t/ha or more.

In the irrigated areas, the average yield has been 3.5 t/ha. With present technology, it is possible to raise the average of irrigated wheat to at least 4 t/ha, with yields of 5.5 t/ha possible by some advanced farmers. Assuming the present wheat area of 3.4 million hectares, an average yield increase to 2 t/ha will result in a national production of 6.8 Mt, which will satisfy the current demand.

With an additional 1.2 million hectares of rainfed area, the domestic wheat area would reach 4.6 million hectares and—with an average yield of 2 t/na—would result in a total production of 9.2 Mt, guaranteeing self-sufficiency into the next century, assuming the current per capita consumption of 46 kg prevails with a population of 180 million people.

Table 7 shows the deficits and surpluses of wheat expected in the year 2000 with the present cultivated areas and with the possible expansion of rainfed wheat in the traditional regions, assuming yield increases to 2-2.5 t/ha and per capita consumption increases to 50-55 kg/year.

Present research results suggest that the projected yields increases are conservative. In addition, farmer adoption of advanced technology has accelerated due to economic factors and the new posture of farmers within the economy.

Wheat as a Component of Human Food

Table 8 shows 1989 Brazilian per capita consumption of wheat, rice, bean, cassava, and maize flour. Wheat consumption has changed over the years—in 1940, it was only 23 kg; by 1960 it had increased to 31 kg; in 1970 it was 36.4 kg; it reached a high of 57.1 kg in 1980; since then it has

Table 7. Possible surpluses or deficits of wheat in Brazil, in the year 2000 as a function of increasing planting area or increasing yield, using the 1987-89 period as a base point.

Year	Area (1000 ha)	Yield (kg/ha)	Production (1000 t)	Seed (1000 t)	Consumption per capita (kg)	Consumption Total (1000 t)	Surplus (+) Deficit (-) (1000 t)
1987-89	3417	1697	5792	550	46	6655	- 1413
2000	3417	2000	6834	550	46	8280	- 1996
2000	3417	2500	8542	550	46	8280	- 287
2000	4600	2000	9200	736	46	8280	+ 184
2000	4600	2000	9200	736	55	990	- 1436
2000	4600	2500	11500	736	55	9900	+ 864

decreased to the present 46 kg (Table 4). The factors influencing consumption have been:

- The increased urbanization of the population.
- Several applied subsidies, especially during the 1972-1987 period.

Both of these factors have favored increased wheat consumption and the substitution of traditional foods, mainly cassava and maize flour. Bean consumption has remained constant.

Trends in Wheat Consumption and Production

On the international level, there is a decreasing trend in per capita consumption in the more advanced countries—wheat products are being replaced by lower calorie foods. In the developing countries, there is an upward trend in per capita consumption caused by cultural factors and influenced by the aggressive policies of exporting countries supplying wheat under favorable trade agreements.

Traditionally, wheat consumption has been greater in the cool and temperate regions and low in the warmer regions where rice and maize predominate. However, in recent times, increased wheat production in the warmer areas has, in turn, increased local consumption. A policy favoring the development of wheat production in warmer areas where its potential may be limited could cause a consumption increase at the expense of rice, maize, cassava, and other tropical food crops. This might not be favorable to local, low income citizens, particularly farmers, because it may reduce markets for other food crops they produce, and they must pay for wheat imported from other parts of the country or from abroad.

Table 8. Per capita consumption of (kg) selected products during 1989.

Rice	73
Wheat	46
Bean	17
Maize flour	17
Cassava flour	14

Source: Bank of Brazil-CTRIN and Ministry of Agriculture-CFP.

In Brazil, wheat consumption is greater in the south along the coast and in large urban areas mainly in the southeast. Table 9 illustrates that per capita consumption is lower in the warm areas (north, northeast, and west central) of the country and greater in the southeast and south.

The increase in per capita consumption in the northeast—the poorest region of the country—has had a harmful effect on the local economy, especially on the poor, small-scale farmers who had their livelihood through cassava production diminished.

General Policies for Wheat Production and Consumption

For many years, the country's economic policy was directed to substituting imports with domestic production with the aim toward self-sufficiency. Actions sometimes were not consistent with this policy—due mainly to a "balance of payments" problem and to keep food costs low. Wheat imports from the USA and Canada came about through agreements where payments were due within 3 years—actually a more favorable situation than for cash loans.

To keep the cost of living low, the Government subsidized wheat consumption several times because the price of this food could be easily controlled because of the Government's monopoly of both domestic production and imports. The subsidy applied during the 1972-1987 period stimulated wheat consumption, increasing its use to the detriment of other basic foods such as rice, cassava flour, and beans. The per capita consumption in 1970 was 36.4 kg, increased during 1980-86 to 49.7 kg, but decreased during the 1987-89 period to 45.4 when the subsidy was reduced and finally terminated.

Despite some contradictions in the wheat policy, it has enabled Brazil to be self-sufficient in wheat—if the Government so desires.

Technical difficulties have been solved such that national wheat yields have increased 2.5-fold in the last 30 years. These advances were possible through the development of improved cultivars, the use of efficient systemic fungicides, increased use of fertilizers, better weed control and soil management, and careful zoning for agricultural practices. Due to these technical advances, yields in Brazil are now comparable to those of other large wheat producing countries (Table 10). Economics and political factors will decide the future of wheat production in the country.

In Brazil, wheat production requires more lime, fertilizers, and fungicides than in many countries, hence, input costs are higher. However, wheat following soybeans in the same year not only lowers overall input costs (estimated at 15%), but makes it possible for farmers to get income from two crops—an advantage over farmers in other countries who depend on one crop each year for their income.

The traditional policy for wheat (stimulation of local production to substitute for imports) was changed, in part, at the end of the last Government

Table 9. Total and per capita consumption of wheat by region, 1972 and 1981.

Region	Total consumption			Per capita consumption		
	1972	1981	Percent change	1972	1981	Percent change
	(t/year)			(kg/year)		
Northeast	654,273 (19.0)	1,302,833 (20.7)	99	22.0	37.5	70
Southeast	1,992,703 (57.7)	3,368,399 (53.5)	69	49.4	71.9	46
South	667,594 (19.4)	1,312,557 (20.8)	97	40.0	69.1	73
North	80,727 (2.3)	183,508 (2.9)	127	22.1	30.8	39
West central	54,703 (1.6)	132,703 (2.1)	143	10.6	17.6	66
Total	3,450,000 (100.0)	6,300,000 (100.0)	83	35.0	55.3	58

Sources: Carvalho (1981) and Calegar and Schuh (1988).
Note: Numbers in parentheses represent the percent share of the total.

period to a policy of giving special attention to the trade balance in South America, especially with Argentina. Included in the trade agreement is the importation of large amounts (up to 2.2 Mt per year) of wheat from Argentina for a period of 5 years. As a consequence, Brazil now will face wheat surpluses because, at the same time that this agreement with Argentina was reached, domestic production was on the rise due to yield increases.

Government authorities wrongly believed that the production increases were transitory due to exceptionally favorable weather; however, the true reason for the increases is farmer adoption of new technology developed through research. These higher yields have stabilized over the last 5 years irrespective of weather.

The new Government favors a more free market, termination of subsidies for production and consumption, and ending its own monopolies for buying and selling wheat by favoring a common market and economic integration with South American countries, particularly Argentina as mentioned earlier.

The World Bank (1990) estimates that the domestic wheat price was 33% higher than the imported price during the 1980-88 period—using the official exchange rate; using the shadow exchange rate, it was only 12.5% higher (Table 11). Over a longer period (1970-1988), domestic wheat had a 24-37% higher price over the imported wheat at the official exchange rate, but the difference was only 8.9% at the shadow exchange rate (Table 11).

The price differences between domestic and imported wheat using the shadow exchange rate indicate that national wheat protection by price was relatively small. Lowering of the consumer prices for wheat products will increase per capita consumption and hence increase the overall demand, but it will also depend on the prices of competitive foods.

A decrease in domestic wheat production not only will directly affect farmers, but also the input costs of the soybean crop—so important to the national economy. All these factors will influence the future national wheat policy.

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Table 10. Average wheat yields (kg/ha) in selected countries.

	1980	1987	1988
Brazil	865	1765	1591
Argentina	1549	1846	1683
Australia	962	1364	1516
Canada	1738	1926	1212
USSR	1597	1785	1760

Table 11. Relative prices of wheat in Brazil. (Imports/local production, %).

Years	Official exchange rate	Shadow exchange rate
1970-88	24.4	8.9
1980-88	33.3	12.5

Source: World Bank (1990).

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Resumen

En los últimos cinco años se han producido cambios importantes en la producción, el consumo y la política de trigo en Brasil. La producción anual durante el período de 1985-1989 fue de 5.5 millones de toneladas, en comparación con 2.2 millones de toneladas durante el período de 1980-1984. El rendimiento nacional medio aumentó de 998 kg/ha durante 1980-1984 a 1,634 kg/ha en 1985-1989. Durante este último período la superficie cultivada con trigo se incrementó en un 30%. El consumo de trigo disminuyó de una cifra máxima de 57 kg per cápita en 1980 a 46 kg en 1989. Estas tendencias respondieron a la política del gobierno de usar, siempre que fuera posible, la producción del cereal para sustituir las importaciones de trigo, al monopolio gubernamental de la compra y la venta de todo el trigo nacional e importado y a la adopción de nuevas tecnologías por los agricultores.

Con el nuevo gobierno brasileño, se ha producido una reciente modificacion de la política, orientada a la integración del mercado con otros países de América del Sur. Brasil ha acordado importar hasta 2.2 millones de toneladas anuales de trigo de Argentina durante los próximos cinco años.

En el decenio de los 80, la producción de trigo fue estimulada por un precio al productor que superaba en un 33% el precio del trigo importado según el tipo oficial de cambio. No obstante, este valor disminuye al 12.5% si se usa el tipo teórico de cambio, que elimina la sobrevaluación de la moneda brasileña. La nueva política gubernamental de permitir que fluctúe libremente el tipo de cambio y una política de comercio completamente liberalizada influirán en la producción y el consumo futuros de trigo.

La producción de trigo en las zonas donde tradicionalmente se ha cultivado podría expandirse a 1.6 millones de hectáreas adicionales en la tierra arable existente, sin competir con otros cultivos. Los rendimientos medios de trigo podrían llegar a 2.5 t/ha. Aun cuando el consumo per cápita crezca a una cifra prevista de 55 kg y la población aumente a 180 millones para finales de siglo, la realización de la producción potencial aseguraría la autosuficiencia en trigo de Brasil.

Wheat Production in Paraguay: Trends, Major Constraints, and Potential

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Abstract

Wheat production increases in Paraguay have been the result of government policy to become self-sufficient in basic food production. All decisions on research, extension, seed production, pricing and commercialization, cheap agricultural credit, and storage have helped toward the achievement of this goal. The significant increase in area planted to soybeans and their resulting production increase have also been a key factor in increasing wheat area to utilize land during the winter cycle. The major wheat production constraints are the erratic temperatures and precipitation that can cause serious disease epidemics in wet and warm seasons. Lack of adequate progress in breeding for resistance to warm climate foliar and spike diseases, such as spot blotch, glume blotch, and scab, has led to intensified use of chemicals. The progress in local breeding efforts is slow but visible. Additional problems of soil degradation and erosion are causing concern and require new tillage technologies and rotation systems. Future progress in this area will help realize the genetic gains made so far. Wheat in Paraguay has become an important part of the agricultural system and, depending on the advances made in developing new technology (varieties and cultivation methods) and efficiency in its cost of production, it will most likely remain the third most important agricultural export crop.

Introduction

Only a decade ago, it was widely believed that Paraguay's marginal environmental conditions would not permit the country's farmers to produce wheat. This opinion was supported by serious disease epidemics and crop failures caused by environmental factors that led many farmers to discontinue planting the crop during the 1970s. The wheat area fluctuated between 8,300 and 59,000 ha during the 1967-81 period during which time yield remained stagnant at about 1 t/ha (Table 1). However, since 1982, both area and yield have been rising steadily. This has allowed Paraguay to become self-sufficient since 1984 and a small wheat exporting country for the first time in 1989. In 1989, 236,400 ha were seeded to wheat. A total of 505,000 t was produced, representing a 100% yield increase over the pre-1982 period. Subsidized wheat flour imported from neighboring countries helps to meet the local consumption requirement of approximately 300,000 t. This flour importation circumstance allowed the export of around 225,000 t of wheat (45% of production) to surrounding Latin American countries and others during 1989-90.

Wheat's geographic location and spread

Wheat is concentrated in the eastern and southeastern regions of the country, especially along the Paraná River Basin. The Departments of Itapua and Alto Paraná, where soil and climatic conditions, as well as farming systems, are relatively better for mechanized agriculture were responsible for 43% and 39% of the country's wheat production in 1989.

In Paraguay, as in other Southern Cone countries, mechanized farming is based on a soybean-wheat rotation system. Wheat is sown in the winter season in May and June and harvested from mid-September

through mid-November. Soybean growing was initiated in the country because it fits well in rotation with wheat (MAG 1967). However, after the excellent soybean performance and the dramatic four-fold increase in soybean prices in the international market in 1974, this crop became a major Paraguayan export. Increase in wheat area in recent years has closely followed the expansion in soybean area (Figure 1). During the 1989-90 season more than 850,000 ha were seeded to soybeans and less than a third of this was occupied by wheat during the following winter cycle.

There are approximately 5,300 wheat growers—most have less than 100-ha farms in total; there are five large corporate farms (MAG 1987). Most wheat flour is made into bread and a variety of homemade products. Approximately 30% is used for pasta products.

Table 1. Wheat area, production, and average grain yield in Paraguay, 1967-89.

Year	Harvested area (ha)	Production (t)	Average yield (kg/ha)
1967	8,300	9,100	1,100
1968	20,900	25,100	1,200
1969	34,300	31,400	915
1970	44,700	47,700	1,067
1971	51,500	54,800	1,064
1972	32,000	17,600	550
1973	20,300	23,000	1,133
1974	32,100	35,200	1,097
1975	23,400	20,800	889
1976	28,800	32,300	1,120
1977	28,500	28,300	992
1978	35,000	38,000	1,100
1979	53,000	59,000	1,072
1980	42,700	46,000	1,077
1981	50,000	54,000	1,042
1982	70,000	70,000	1,000
1983	75,000	107,000	1,426
1984	96,000	139,000	1,450
1985	126,900	184,600	1,455
1986	153,700	233,500	1,519
1987	162,000	284,000	1,750
1988	189,900	315,000	1,658
1989	236,400	505,000	2,136

Source: Direccion de Investigacion y Extension Agropecuaria y Forestal. Ministerio de Agricultura y Ganaderia, Paraguay.

Production Trends

Initial period (1967-72)

Although historically wheat production in Paraguay was started by Jesuit priests during the colonial period, it never became an important crop. In recent times, however, considering the importance of wheat in the diet and its export value, local production was re-initiated. Spring bread wheat production started increasing with the commencement of the National Wheat Program (NWP) in 1967 (MAG 1967). In fact, mechanized grain production started in the country with the NWP. Before 1969, there were less than 600 tractors, most of them utilized by lumber companies and large cattle ranches. The NWP implemented an aggressive policy of investment incentives, especially in the early years. These included marketing regulations, an officially fixed wheat price, access to long-term, low interest

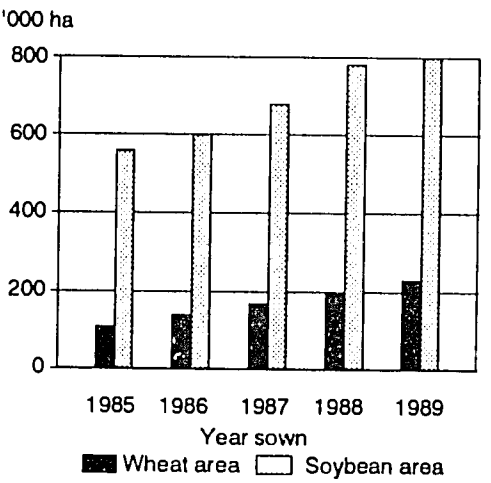


Figure 1. Wheat and soybean area expansion in Paraguay, 1985-89.

Source: UEAE/DIEAF/MAG.

credit from the official bank (Banco Nacional de Fomento) for land improvement, farm buildings and grain storage facilities, and machinery, as well as short term loans for up to 80% of the operational costs of the crops. Other additional services were provided by the Ministry of Agriculture, included an the active research and extension system, the creation of the National Seed Service (Servicio Nacional de Semillas, SENASE) to provide certified seed, and a network of regional grain storage terminals with a 29,090-t capacity in addition to the facilities owned by cooperatives and milling companies at that time. These actions provided a solid base to start and resulted in a dramatic increase in wheat cultivation in the first 5 years. Most of the first wheat growers were inexperienced cattle ranchers whose farms were scattered across different ecological areas.

The program was initially based on a group of varieties selected from the International Spring Wheat Rust Nursery (ISWRN) and released in 1965 (Table 2). These varieties exhibited reasonable adaptation and yield potential ranging from 1000 to 1500 kg/ha at the farmer level. However, they were tall, lodging-susceptible and late. The first high yielding semidwarf, 214/60, a Mexican line selected from the ISWRN nursery, was released in 1970. This cultivar outyielded the earlier varieties because of its rust resistance, fertilizer response, and shorter cycle; by 1972, it had become the most cultivated variety in the country. That year was unusually wet and wheat seeding was delayed, which resulted in an area decline of about 35%. The wet, warm weather during that crop cycle provided conditions for the development of severe

Table 2. Commercial wheat varieties released in Paraguay, 1965-88.

Variety	Cross	Origin Nursery	Release Institution	Year
Centenario	LEE/FN	USDA	IAN	1965
No. 6	FN/K58//N 150	USDA	IAN	1965
Boquerón	NS 4021//K338 AC/ND 52	USDA	IAN	1965
No. 9	K338 AA//NS3880.191/ND 52	USDA	IAN	1965
No. 11	K338 AA//NS3880.191/ND 53	USDA	IAN	1965
214/60	KT 54/N10B21	Mexico	IAN	1970
281/60	KL.COMETA//NEWTHATCH/MEN-TANA/3/MENKEMEN/4/MAYO54	ICA	IAN	1970
Itapúa 1	NGF/2*FR/4/N/NT//NT/K/3/BG/5/FR	Mexico	CRIA	1972
Itapúa 5	SON 64/KLRE	CIMMYT	CRIA	1974
Naica	SON 64/TZPP//NAI 60=JAR'S'	CIMMYT	CRIA	1974
Timgalen	AGUILERA/KENIA//MARROQUI/ SUPREMO/3/GB/4/WINGLEN	U.Sydney	IAN	1978
C-7605	J9281.67/LR 64 A	FECOTRIGO	IAN	1979
Itapúa 25	PI/3/LR64//TZPP/KNOTT 2	CIMMYT	CRIA	1979
IAN 5	KL.LUC *4/Y 53//IFLE 9996	CIABB	IAN	1980
IAN 7	CNO/PJ//CAL	UFPEL /CIMMYT	IAN	1981
Cordillera 3	KVZ/BUHO'S'//KAL/PB	CIMMYT	IAN	1982
Cordillera 4	AEPOGLOM/II 5427 (=MN72131)	USDA	IAN	1984
Itapúa 30	JUP/ALD'S'	CIMMYT	CRIA	1985
IAN 8-Pirapó	BOBWHITE'S'	CIMMYT	IAN	1987
Itapua 35-Aperea	CMH 74.A74/PEL 72384//ATR	CIMMYT	CRIA	1988

epidemics of foliar diseases, especially spot blotch (*Helminthosporium sativum*) and glume blotch (*Septoria nodorum*), resulting in an estimated 70% loss of the crop nationally. Because of this farmers were not encouraged to grow wheat in the following years (Table 1) (Alarcón 1974).

Critical period (1973-78)
During this period, the wheat area stabilized between 20,000 and 30,000 ha. In 1975 another severe epidemic of glume blotch and head scab (*Fusarium graminearum*) infected the crop (MAG 1976). The damage caused was lower than in 1972 due to the large area planted to the variety Itapua 1—a low yielding, but disease resistant cultivar that performed better in the first epidemic. However, the argument still persisted that the Paraguayan climate was unsuitable for wheat. Due to the discouraging effect caused by these epidemics, many of the original wheat farmers discontinued growing the crop (MAG 1977, 1980).

The first failures started with farms located on the most marginal lands, such as the semiarid central Chaco or the poorly drained lowlands in eastern Paraguay. Later, in the mid-1970s, many farmers located on the sandy latosolic red-yellow soils of Misiones in the south gradually stopped arable farming because the soils were exhausted and highly acidic. Wheat cropping finally settled in the southeastern region where it is still increasing in area. Moreover, wheat benefitted from one of the most significant events of 1970s and 80s—the massive land clearing and settling of forest lands in the southeast. Soybeans were the main cash crop, but once the land was fully mechanized after clearing of the forest residues, wheat became the main winter alternative.

The complexity of the problems already mentioned stimulated the identification of germplasm from different sources—especially materials from Brazil and Uruguay (Torres and Pedretti 1981). Due to the extreme susceptibility to foliar spots and head scab of the Mexican varieties and CIMMYT lines distributed in the 1960s and 70s, most of this germplasm was discarded. This effort resulted in the identification and release of more resistant or tolerant varieties such as IAN 5, IAN 7, and 7605 (Table 2). However, at the same time, it became clear that this regional germplasm had narrow adaptation. Although better tolerance to foliar spots and head scab was available in this material, its leaf and stem rust resistance was less stable, yield potential intermediate, and was susceptible to lodging. Starting in 1975, tests conducted on chemical control of diseases led to the recommendation of fungicide application to the commercial crop to ensure crop survival.

Recovery period (1979-83)
This period was characterized by the strengthening of the national wheat program with increased emphasis on chemical disease control. This became one of the most important factors for stabilizing wheat production. Contact fungicides used earlier were replaced by more efficient systemic fungicides. Triadimephon (Bayleton) was one of the most widely utilized systemic fungicides. Following a heavy epidemic of *Helminthosporium sativum* (syn. *Bipolaris sorokiniana*) in 1982, it was replaced by the newer wide spectrum fungicides based on triazoles, such as propiconazole.

The 1978 opening of the CIMMYT outreach office in Chile for the Southern Cone of South America resulted in the availability of better adapted CIMMYT germplasm. This was accomplished by:

- Redirecting part of the CIMMYT headquarters breeding program to meet the demands of this region. This

was possible by increasing the multilocation testing to identify genetic material with better performance, especially in the marginal, warmer areas.

- The implementation of a joint Brazil-CIMMYT shuttle breeding program for development of germplasm tolerant to aluminum toxicity prevalent in the region's acid soils. These materials also demonstrated increased disease resistance to the indigenous foliar pathogens.

- The rapid release and cultivation of new germplasm carrying the 1B/1R translocation (especially the Veery sister lines) as a breakthrough for disease resistance and agronomic performance. In Paraguay, the identification of Veery #3 (= Cordillera 3) as the most promising line led to 60 t of seed being imported from Chile in 1982. This seed greatly accelerated farmer adoption of this variety. In the following years, thanks to the valuable cooperation of Chile's Instituto Nacional de Investigacion Agropecuaria (INIA), summer seed increase in central Chile facilitated the availability of larger volumes of seed for new varieties such as Cordillera 4, Itapua 30, and Itapua 35.

Take-off period (1984-89)
This period is characterized by an unprecedented increase in wheat area and production and doubling of the national average yield to more than 2 t/ha. This was undoubtedly the combined effect of improved varieties, widespread use of fertilizers and efficient fungicides, along with a series of comparatively good growing seasons. The continuous policy support given by the Government and the ongoing land settlement process expanding the agricultural frontiers of both soybean and wheat were also of key importance.

Major Wheat Production Constraints

Major constraints limiting wheat production in Paraguay can be grouped in two categories: technical and policy. Technical limitations, both biotic and abiotic, are imposed by environmental factors. Policy decisions deal primarily with insufficient infrastructure (asphalt roads, long-term storage capacity), unavailability of inputs at the correct time, scarcity of specialized farm machinery, and the availability of support prices.

Abiotic stresses
Abiotic stresses, which can be only partially solved by wheat breeding and crop management, can be divided into soil and climatic aspects.

Soils—Currently, more than 90% of the wheat crop is sown on basalt-derived soils such as Ultisols and Oxisols (Chiba et al. 1987, Yamanaka et al. 1987). While these soils are the best suited for mechanized agriculture because of their physical characteristics, they are highly leached with various degrees of acidity: pH 5.0-6.5, low-to-medium base saturation capacity, and low available phosphorus (1-3 ppm). The amount of wheat produced on sandstone-derived, podzolic soils with sandy-loam texture (San Pedro, Caaguazú, and western Canindeyú Departments) is decreasing over time (MAG 1987, Secretaria Tecnica de Planificacion 1983) due to the soils' high susceptibility to hydric erosion and the occasional presence of exchangeable aluminum in the sub- and topsoil.

From a crop management perspective, conventional tillage in the continuous soybean-wheat rotation system causes progressive soil degradation and erosion. After a few years of mechanized farming, soil compaction can be observed in both kinds of soils, while surface crusts following heavy rainfall (> 150 mm/day)

are frequent on sandy soils. Organic matter diminishes from 3-4% to 1-1.5% during the 5 to 7 years following forest clearing, and to mere traces, particularly in sandy soils with continuous cropping. Despite low initial fertility, the maximum economic response to fertilizers in most cases is observed up to 50-50-0, indicating the presence of additional limiting factors (Caceres et al. 1988).

Aluminum toxicity is not a common production constraint in Paraguay. However, continuous soybean-wheat cropping with conventional tillage tends to increase acidity, aluminum toxicity, and calcium deficiency (Yamanaka et al. 1987) and iron toxicity in northern Itapua Department. Liming is not widely practiced because of high costs, unavailability of large amounts of lime, and scarcity of long-term credit.

Climate—Unstable climatic conditions during the wheat growth cycle represent another source of abiotic stresses. Most of the wheat crop is located in the continental tropical/subtropical mesothermal humid region (Tavella 1971). The climatic variability and unpredictability are due more to irregular rainfall distribution than to temperature variation, given the small difference in latitude (19-27°S) and elevation (80-500 masl).

Annual mean temperature ranges from 21°C in the south (Itapúa) to 21.6°C in the northern wheat growing region (Canindeyu). Seasonal variation for both maximum and minimum average temperatures approaches 11°C between winter and summer. Whereas seasonal and regional differences exist, the temperature variation during the winter better characterizes the stress placed on the crop. High and low temperatures alternate weekly during the whole wheat growing cycle, with extreme temperatures ranging from less than 0°C to more than 30°C within a few days. On a daily basis, a 10°C day/night difference is common. Winter frosts (record low temperature is -6.7°C in Itapua) represent another risk with erratic frequency. Depending on polar airmass movement, temperatures around 0°C can occur at any time primarily during the first part of the wheat growing season. Although the higher frequency is concentrated during June and July, rare late frosts can severely harm the crop during the reproductive stage.

Wheat is a rainfed crop in Paraguay. Although precipitation during the wheat growing season is high (765 and 810 mm May-October averages for Vjhovy and Capitan Miranda, respectively), its erratic distribution and high intensity, causing serious runoff and soil erosion, determine the alternate periods (2-3 weeks) of mid-season drought. A considerable part of the total rainfall occurs during the harvest season (October), causing grain washing, decreased test weight, and occasional sprouting.

There is a wide diversity both in distribution and the amount of total rainfall recorded during the year. The rainfall received during the winter season is critical in determining the annual amount of approximately 500 mm received in the north and 1700 mm recorded in the south, which explains the absence of a dry period in Itapua and the presence of a marked dry period (June-September) along the northwestern border with Bolivia.

Potential evapotranspiration ranges from a minimum of 1100 mm in the southeast (Itapúa) to a maximum of 1500 mm in the north (Chaco). Although most wheat growing areas are located in the humid region of the country, at least 10% of the crop is located in the water-deficit region and suffers from drought, especially during July-August.

Biotic stresses

Environmental conditions discussed above determine biotic stresses, especially disease epidemics that severely reduce wheat production in abnormally wet years (Torres and Pedretti 1981).

Diseases—Although genetic resistance has provided effective control of stem rust in the new commercial varieties, leaf rust epidemics are still quite prevalent (Table 3). In addition, powdery mildew occurs frequently from tillering to flowering stages in the drier regions and years. Foliar diseases such as spot blotch (*Helminthosporium sativum*), tan spot (*H. tritici-repentis*), glume blotch (*Septoria nodorum*), and bacterial stripe (*Xanthomonas campestris* pv. *undulosa*) cause severe yield losses in the wetter years, and a considerable constraint to grain yield and test weight in most years (Viedma and Bozzano 1986, Viedma and Delgado 1987). Head scab (*Fusarium graminearum*) is a serious disease in years when wet periods occur at flowering (Viedma 1987).

Genetic resistance has been the most effective control strategy, especially for the rusts and powdery mildew. While the stability of resistance has been maintained for stem rust, it is not so in the cases of leaf rust and powdery mildew. Similarly, resistance to necrotrophic diseases, although improved, is not yet at a high level (Table 4). Resistance to head scab available in Chinese germplasm is currently being used in a cooperative shuttle breeding program with CIMMYT with the objective to incorporate this resistance into superior germplasm. However, at the farmer level, chemical control of diseases is one of the key agronomic practices being used. It has been observed that, in general, late-seeded crops are more affected by diseases than normal seeded fields.

Insect pests—Aphids constitute the most important and prevailing insect pest threat to wheat in Paraguay. Greenbug (*Schizaphis graminum*), widespread in all areas, causes serious damage to the crop

Table 3. Prevalent wheat diseases in Paraguay, 1972-89.

Disease	Year																	
	1972	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
Leaf rust	x	x	x	x	x	x	x	x	x	x	xx	x	x	x	x		x	
Stem rust	x	x				x	x	x	x	x								x
Powdery mildew					x	x							x			x		x
Leaf spot	xx			x	x				x		xx							x
Tan spot																x	x	xx
Glume blotch	x			x											x			
Head scab	x			xx							x			xx				xx
Bacteria											x			xx	x			

x = Presence of disease observed, xx = Severe epidemic causing economic losses.

at the early vegetative stage (Granowski 1974). *Sitobion avenae* usually appears at heading especially in dry years. Three other species, *Rhopalosiphum padi*, *R. maydis*, and *Metopolophium dirhodum*, are of lesser importance. It has not been possible to associate aphid infestation with the occurrence of virus diseases, but the damage caused seems to be lower than in more temperate environments. Genetic resistance to aphids, especially greenoug, represents one of the possible strategies for their control.

Infrastructure and Policy Constraints

Considering the land settlement in the new areas and rapid expansion of agricultural frontiers, insufficient infrastructure development such as paved roads, adequate long-term storage facilities, etc., are serious constraints at the production level (Secretaria Tecnica de Planificacion 1983). Given the climatic conditions of Paraguay, present dirt roads and their network linkage to paved roads are a serious obstacle to efficient movement of harvests to commercial centers.

Inadequate storage capacity is another consequence of the rapid growth. While the private sector has made significant investments in building a network of silos and warehouses (1.1 million ton total capacity) over the last 2 decades, there is still a temporary shortage when soybeans for export and wheat for long-term storage overlap each other during March-August.

The unavailability of critical inputs at the proper time, especially those subsidized by the government, has been a serious constraint. Lack of timely approval of subsidized credit to import fertilizers, pesticides, and farm machinery usually delays their procurement which leads to lower production. Lack of specialized farm machinery, such as subsoilers, chisel plows, and no-till drills, have kept the current soil management practices in place, thereby further degrading the soil

Table 4. Reaction to the main diseases of commercial wheat varieties, recorded at the field level. Paraguay, 1990.

Variety	Rusts Leaf	Powdery Stem	Spot Mildew	Glume Blotch	Head Blotch	Bacterial Scab	Disease
Itapua 25	MS-S	MR-MS	MR	MS	MS	MR	MS
Itapua 30	S	R	S	MS-S	S	MS-S	MS-S
Itap.35, Aperea	R	R	R	MS	MR	MS	MS
Cordillera 3	S	R	MS	MS	MS	MS	S
Cordillera 4	R-MR	R	VS	MS	MS	S	S
IAN 7	MR	MS	MR	MR	MS	MS	MR
IAN 8, Pirapo	R	R	MS-S	MR	MR	MS	MS

R = resistant, MP = moderately resistant; MS = moderately susceptible, S = susceptible, VS = very susceptible.

and depressing grain yields in older fields. There is an urgent need to reverse this process before it is too late.

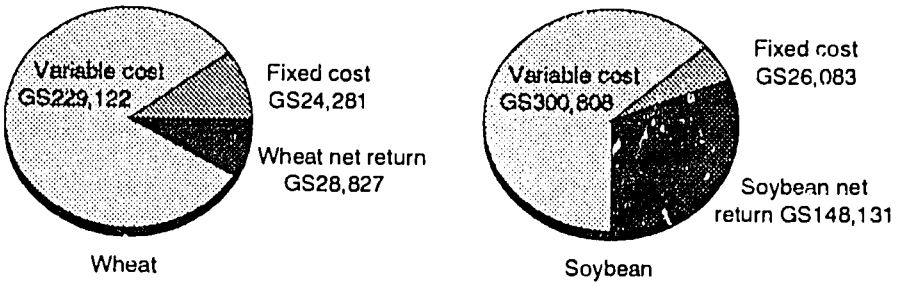
Lack of an adequate commercialization policy has allowed mushrooming of various levels of intermediaries during the harvest period, which even further reduces the small profit margin a farmer can expect from wheat. Farmers organized in large cooperatives have had to wait long periods before delivering their product to the mills, thereby incurring additional storage costs as well as accepting deferred payments with little monetary adjustments. This is seriously affecting the morale of wheat farmers, although there are few arable alternatives for the winter season crop. The elimination of officially fixed prices during 1989 resulted in much lower farm gate prices than expected. The profit margin from wheat (Figure 2) when compared to soybeans will be a decisive factor in the extent of wheat's future expansion.

The Future

As mentioned earlier, Paraguay reached self-sufficiency in wheat production in 1986 and became a small exporter for the first time in 1989. Further expansion of wheat will depend, to a large degree, on how the constraints discussed above are handled or resolved. While there is no clear substitute for wheat during the winter cycle, the present system of soybean-wheat rotation must experience a change where new crops/green manures will be brought into the rotation system to permit long-term sustainability of the country's agriculture.

There are an estimated 4.5 million hectares of basaltic soils in eastern Paraguay that can be utilized for mechanized grain production. Currently, only about 25% of this is being farmed. In the past, the relatively slow pace of land clearing through the burning of forest residues has allowed full mechanization only after 3 to 5 years. However, the new land settlement concerns of large-scale farmers are currently accelerating the pace of land clearing and opening vast areas of previously forested land. An estimated 400,000 hectares of land were cleared during 1989 alone. Once these areas come under the plow and extensive farming practices are adopted, the area under wheat is likely to experience a dramatic increase.

The negative side of wheat expansion includes such factors as inexperience of a large segment of the new farmers,



Price GS/kg: 140 (Wheat), 190 (Soybean)
Exchange rate: Approx. GS1200 to US$1.

Figure 2. Comparison of wheat and soybean profitability, Guaranies (GS)/ha, Paraguay, 1989. Source: CIMMYT/MAG.

machinery scarcities (especially tractors and combines), the short period between soybean harvest and wheat seeding (or vice versa), and finally the marginal profitability of wheat.

Cost of production

Until 1988, subsidized inputs (oil, fertilizers, insecticides, herbicides, and fungicides) through a differential US dollar/guarani (GS) exchange rate for imports kept production costs reasonably low. However, the initiation of a free market economy in 1989 caused an estimated 30% increase in the cost of production. Farmer experience, resulting in doubling of average grain yield over the last 8 years, has been of key importance in maintaining market competitiveness despite high increases in production costs. The free marketing policy, implying no official price for internal market or for export, started during the 1989 harvest season, and suffered its first setback early in 1990 when local millers used delaying tactics in receiving the harvest as well as in making payments to farmers. In addition, new exporting agents had no clients or influence. As a result of this confusion, farmers received a 17% lower price in fixed currency (Figure 3) than the year before, resulting in serious demoralization. This may be a particular case of only 1 year and may not be repeated as more experience in handling surpluses is gained. However, considering the new policy, the cost of production is likely to go up further, making existing profits even more marginal.

Despite the commercialization problems of 1989, the area under wheat did not decrease substantially during the 1990 crop season. The expectations of export possibilities and higher export prices have encouraged farmers to maintain their wheat areas at least for the time being. However, another commercialization debacle like 1989 will seriously erode the gains made so far. The landlocked geographic location of Paraguay adds higher transport costs compared to traditional coastal wheat exporting countries. Comparative advantages favor exports to neighboring Latin American countries more than overseas markets. However, marginal profit is progressively becoming the most critical factor at the farmer and national levels. An index price and market fluidity both at the internal and export levels will probably be of key importance for any large-scale increase in the wheat production.

Grain yield

There is potential to further increase the average grain yield in Paraguay. Experiment station yields of 4.5 t/ha and farm yields of 3 8 t/ha have already been achieved. For 1989 this leaves a wide gap of 2.1 t/ha between the potential and the current national average grain yield. To close this gap, a combination of improved agronomic practices—including concepts of sustainability, germplasm with wide spectra of resistance to diseases, enhanced tolerance to abiotic stresses, and a higher efficiency in production inputs—will be essential.

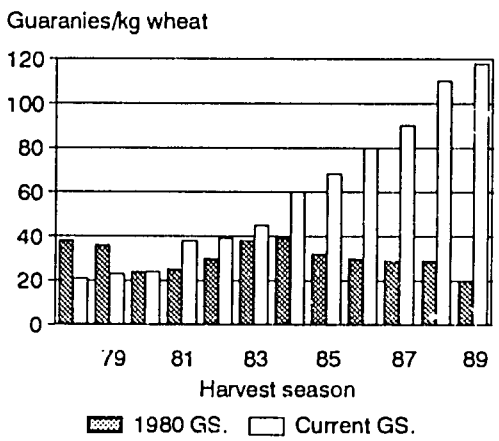


Figure 3. Wheat price trend based on constant (1980 base year) and current guaranies (GS)/kilogram, Paraguay, 1989.

The increasing use of direct drill machinery without concern for soil compaction, soil amendments, and crop rotation concepts is already jeopardizing production, especially by diseases such as tan spot, which oversummers on wheat residue mulch thus providing a large quantity of primary inoculum the following winter. Such practices, if continued, are likely to have serious effects on future grain yields. The strategic use of more efficient wide spectrum fungicides is potentially important to complement the lack or breakdown of resistance to prevalent diseases. Genetic resistance already detected is in the process of being transferred, despite the fact that the inheritance mechanism is unclear or not known. Furthermore, weather unpredictability, allowing erratic disease selection under field conditions, results in slow progress. Germplasm better adapted to abiotic stresses, such as the combination of midseason drought and high temperatures throughout the growing cycle, is also slow in development. As a result, germplasm development for high yield potential will essentially be a slow process, although substantial gains are expected in the mid-term.

In conclusion, there is little doubt that Paraguay can potentially further increase wheat production. Its realization will depend, not only on the new technology developed by research to increase grain yield to fill the gap between potential and existing farm yields, but also on policy decisions especially with respect to infrastructure development, pricing policy, and easy commercialization (export facilities). Wheat production is likely to keep on increasing in the future, but its rate will depend on the mixture of elements discussed in this paper.

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Resumen

Los aumentos de la producción de trigo en Paraguay han sido el resultado de una política gubernamental para alcanzar la autosuficiencia en la producción de alimentos básicos. Todas las decisiones sobre la investigación, la extensión, la producción de semilla, la fijación de precios y la comercialización, los créditos agrícolas baratos y el almacenamiento, han estado orientadas a lograr esta meta. El considerable aumento de la superficie sembrada con soya y el resultante crecimiento de la producción han constituido un factor clave del incremento de la superficie cultivada con trigo con el fin de utilizar la tierra durante el ciclo invernal. Las principales limitaciones de la producción de trigo son las temperaturas y la precipitación pluvial erráticas, que pueden causar graves epifitias en las estaciones cálidas y húmedas. La falta de un progreso adecuado en el mejoramiento para obtener resistencia a las enfermedades foliares y de la espiga frecuentes en los climas cálidos, como la mancha foliar, el tizón de la gluma y la roña, han llevado a la intensificación del empleo de sustancias químicas. El progreso en las actividades locales de fitomejoramiento es lento pero evidente. Los problemas adicionales de la degradación y la erosión del suelo causan preocupación y exigen nuevas tecnologías de labranza y sistemas de rotación. El progreso futuro en esta área contribuirá a aprovechar los avances genéticos logrados hasta el momento. En Paraguay, el trigo se ha vuelto una parte importante del sistema agrícola y, dependiendo del progreso alcanzado en la obtención de nuevas tecnologías (variedades y métodos de cultivo) y la eficiencia en relación con el costo de la producción, muy probablemente el cereal seguirá ocupando el tercer lugar entre los cultivos de exportación más importantes.

Global Status and Recent Progress in Breeding Wheat for the Warmer Areas

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Abstract

The recent trends of wheat consumption and importation by developing countries in the warmer regions are causing serious concern and are a primary reason for them to increase local wheat production. Since the early 1970s, varieties have been selected from international nurseries and released for commercial production in the warmer regions. During the period of the project sponsored by the United Nations Development Programme (UNDP), improved germplasm, adapted to these regions, with 10-20% yield superiority over Anza, has been identified and released. Superior germplasm for other important characters such as resistance to biotic and abiotic stresses, although identified, still need to be further combined to develop overall adapted varieties. Major successes have been achieved in developing varieties for acid soils with aluminum toxicity and a wider base of rust resistance. However, resistance to drought, heat, spot blotch, and scab need further improvement. While increased yield potential and stability, combined with disease resistance, would be the immediate goal for the future wheat breeding programs, exploitation of additional genetic variability, knowledge of genetic bases of key characters, and the employment of accelerated screening techniques in cooperative efforts within and between national programs, and CIMMYT, will be critical to the development of germplasm.

Introduction

"Tropical wheat" is simply a convenient way of saying "wheat that may perform well in warm environments that are marginal production areas due to their heat-related biotic and abiotic stresses." While a few countries representing these marginal environments such as Brazil, China, India, Pakistan, and Paraguay have been able to meet their rising demand by increasing domestic wheat production, a large majority have had to depend on increasing imports. These countries, lying in the tropical belt between 23°N and 23°S latitudes, include nearly all of sub-Saharan Africa, Southeast Asia, Central America, the Caribbean (except Mexico), and the Andean region and the central part of the Southern Cone in South America. Together, these countries have nearly 1.3 billion people—almost a third of the developing world's population. Meeting their increasing demands for wheat and wheat products has serious economic implications.(Byerlee and Longmire 1986)

During 1986-88, these countries imported nearly 27 million tons of wheat annually (Table 1), draining nearly US$5.5 billion from their economies. During 1979-88, the growing imports were responsible for 88, 72, and 56% of the total wheat consumption in Africa, Asia, and Latin America, respectively.

The constraints to wheat production and needs for germplasm improvement specifically designed to these marginal environments have been discussed during two earlier conferences. "New seed" is only a component of the total technology, but is one which is accepted first and probably with least resistance by the farmers. In this paper, we will try to

summarize the progress achieved in the germplasm improvement and its availability to the warm environments.

Definition of Tropical Environments

Fischer (1985) defines the tropical (nontraditional) wheat environments as "characterized by short winter photoperiods (11 to 12.5 hours) with high temperatures." The mean temperature for the coolest month varies from warm (15°C) to hot (20°C) to very hot (25°C). From a breeding standpoint, potential warm environments for wheat growing can be divided into two major classes based on humidity levels, i.e. dry and wet:

- Hot and dry environments, such as Wad Medani, Sudan; Kano, Nigeria; Indore, India; and Brasilia, Brazil, all have different temperature regimes effecting physiological processes of the plant. However, all these locations have low relative humidity during the wheat cycle leading to virtual absence of diseases. Most of these environments are irrigated and have no major soil problems. Boron deficiency recognized in some areas is easily corrected. As a result, high yield potential and adaptation to the high temperature conditions are major breeding objectives in these areas.

- Hot and humid environments, such as Los Baños, Philippines; Dhaka, Bangladesh; Mbala, Zambia; and Santa Cruz, Bolivia, all have high relative humidity throughout the crop cycle and consequently severe disease epidemics occur making wheat production much more difficult. In spite of receiving sufficient rainfall to allow adequate wheat production, its irregularity causes frequent droughts in most of these areas. Many of the soils are acidic in nature and carry toxic levels of aluminum and manganese that inhibit wheat growth unless it carries resistance to these factors. Breeding objectives for these areas vary from yield potential to yield stability and resistance to an array of diseases. Resistance to toxic elements present in the soil or other factors such as waterlogging or salinity further complicate the situation.

Table 1. Wheat imports by developing countries in the warmer regions, 1961-65 through 1986-88.

Continent	Imports ('000 t)		
	61-65	71-75	86-88
Africa	785	1,638	3,445
Asia	11,766	12,405	17,892
Latin America	3,424	4,573	5,597
Total	15,975	18,616	26,934

Source: FAO data files.

Germplasm Improvement

Historical background

The international nursery network during the 1960s and 70s allowed the identification of superior varieties adapted to some of the warmer regions. Early maturing germplasm such as Sonora 64, Inia 66, and Sonalika found immediate acceptance in the warmer parts of the traditional wheat regions or for late sowing conditions. Adapting well to the 90- to 100-day cycle of these areas, they outyielded older or longer cycle varieties. However, wider testing has demonstrated some advantage in favor of germplasm of intermediate cycle such as Siete Cerros, Anza, Jupateco 73, and Anahuac 75 in parts of Africa and South America, but not in Asia.

UNDP/CIMMYT program
Support of the United Nations Development Programme (UNDP) started in 1982 and was extended in 1987 and again in 1990 has enabled CIMMYT to expand research on the development of high yielding, disease resistant, semidwarf wheats adapted to the warmer, subtropical areas of the world. While supporting the project strongly for the benefits it may bring to those countries in warmer regions interested in wheat production, Mashler (1985) also pointed to its higher risk in comparison to conventional breeding programs, an indication that there is no guarantee of success.

The genetic advances made by research through international collaboration during the last 8 years have resulted in the spread of a new set of varieties and germplasm of higher yield potential across three continents. In several countries of South America such as Argentina, Bolivia, Brazil, and Paraguay, the new varieties have not only increased yield, but also helped reduce the cost of production, by increasing the genetic resistance to diseases thereby, decreasing the use of chemicals for disease control. In some countries of Asia (Thailand, Philippines, and Vietnam), the new germplasm has allowed commercial production to become a realistic goal.

Results Achieved

Breeding for agronomic characters
Adaptation and yield stability—Large-scale international testing of advanced lines from Mexico during 1960s and 70s allowed the identification of superior germplasm, mainly of Mexican origin, adapted to the warmer regions. During the 1980s two special nurseries, the Hot Climate Wheat Screening Nursery (HCWSN) assembled by CIMMYT/ Thailand and the Southern Cone Advanced Line Nursery (LACOS) from the PROCISUR (Cooperative Research Program of the Southern Cone)/CIMMYT, Paraguay, increased horizontal germplasm exchange between collaborators. CIMMYT/ Mexico initiated specific nurseries for heat, helminthosporium, scab, and the warmer areas to distribute promising lines to the target areas. The first varieties originating from crosses between spring and winter wheats added tremendously to the adaptation in several warm environments. Several varieties originating from these materials, such as Veery, Buckbuck, Kea, Bulbul, Punjab 81, and Opata 85, have been released. The yield improvement of the newer germplasm compared to Anza (an old variety adapted to warm areas) is shown in Figure 1. Although the average yield of Anza in 11 warm region locations was much superior (+16%) to the average of all lines included in the 5th ISWYN (1968-69), it was very similar to the nursery average yield in the 14th (1977-78) and the 24th (1987-88) ISWYNs. This demonstrates an overall upgrading of germplasm adaptation to the warm

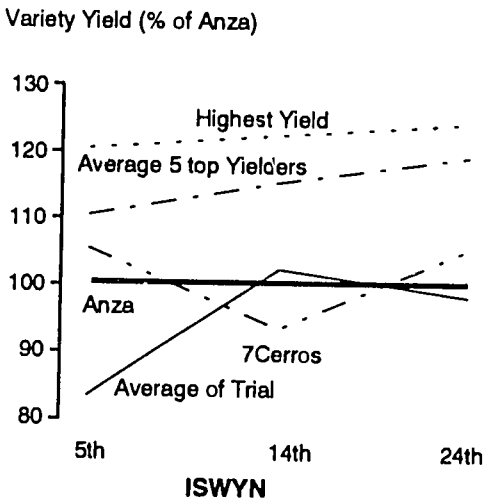

Figure 1. Yield potential of selected germplasm compared with Anza in the warm locations of the International Spring Wheat Yield Nursery (ISWYN).

environments. During the same period, the average yield of the top five lines, compared to Anza, increased from 110 to 120%. However, a mere 5% improvement in the yield potential of the highest yielding entry compared to Anza over a 20-year period reflects the serious limitations posed by these environments.

The stability analysis run over the data set of the 24th ISWYN (1987-88) (Figure 2) shows that newer germplasm such as Seri 82, Kauz, and Caete are not only superior to Anza in the low yielding warm environments, but also outyield it when the environment improves. This is very important for the marginal environments because of their inherent instability due to variable climatic conditions.

Drought tolerance—About a third of the area planted to wheat in the developing countries suffers from moisture stress at one stage or another. In the past, semidwarf wheats of CIMMYT origin or their derivatives distributed through the international nursery system covered 45% of the 300-500 mm moisture environments and 21% of the environments with rainfall less than 300 mm (CIMMYT 1988). These early efforts identified some varieties, like Siete Cerros, which out-performed the local and well known drought tolerant varieties such as Gabo, C306 and C273 (Figure 3) (Pfeiffer 1988).

There was no systematic effort to select segregating generations under drought stress until the early 1980s. At this time, the selection under reduced irrigation conditions in the Yaqui Valley of Mexico alternating with a summer generation on the sandy soils of Huamantla in the highlands of Mexico allowed the selection of materials that should be specifically tolerant to drought stress.

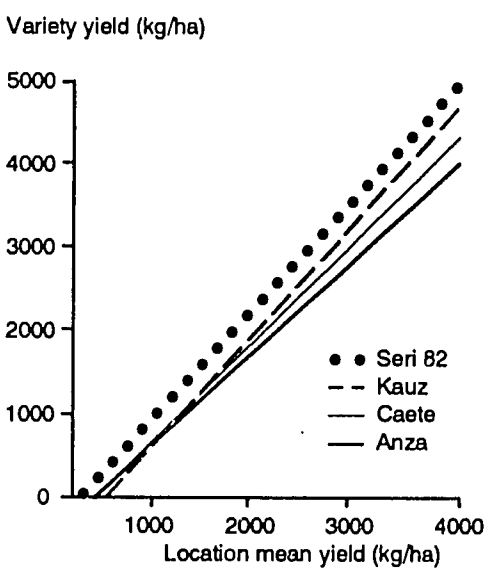

Figure 2. Yield stability of Seri 82, Kauz, and Caete compared with Anza in ISWYN 24 at 11 warm locations.

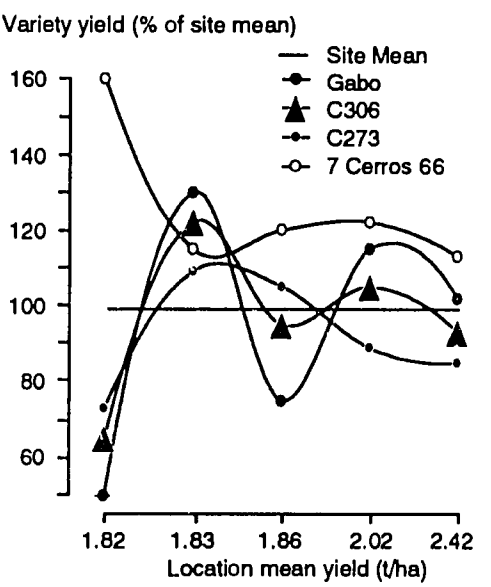

Figure 3. Yield of Siete Cerros 66 compared to the yield of C237, C306, and Gabo in drought stress environments of ISWYN 4, 1967-68. Source: Pfeiffer (1988).

Although it has not been possible to fully evaluate the resulting germplasm under different stress environments, the preliminary results show no advantage of selection under stress (Figure 4). The no-stress group seems to offer higher genetic gains for both stress and nonstress environments, whereas the stress group has lost the yield potential and response to high moisture availability.

Similarly, in a controlled irrigation experiment conducted by agronomists (K. Sayre, pers. comm.) at CIMMYT/Mexico, it was demonstrated that germplasm selected under no drought stress can outperform varieties known for their adaptation to drought (Table 2).

The alternate selection of germplasm under irrigated and rainfed sites and multilocation testing have resulted in broad adaptation in the CIMMYT germplasm. This methodology has been able to produce cultivars adapted to widespread semiarid rainfed conditions such as Kalyansona in India, Marcos Juarez INTA in Argentina, Pavon 76 and Barani 83 in Pakistan, and Galvez 87 in Mexico. Research data generated at CIMMYT and analysis of ISWYN results give conclusive evidence of correlated selection response and progress over time (Figures 5-7).

While the empirical approach of using grain yield under stress environment has given excellent results in breeding for drought tolerance, more information regarding the agroecological parameters of the target environments and the relationship between drought stress patterns in crop performance and associated drought characters will help make further advances.

Heat tolerance—Rawson (1988) believes that high temperature per se has minimal effects on the potential number of organs such as leaves, tillers, ears, spikelets, and florets produced by the plant. That is, yield will be little affected by the accelerated growth caused by the high

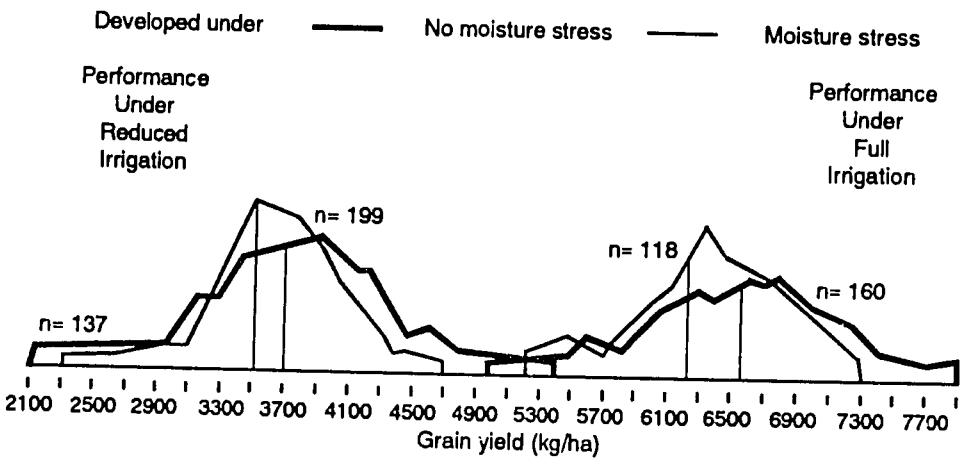

Figure 4. Frequency distribution for grain yield of germplasm developed under different moisture regimes evaluated with and without drought stress conditions (Yaqui, 1987-88).

temperatures if other crop growth factors such as water supply and nutrition are in optimum supply. However in practice, the prediction of need and the short time to supply inputs under these accelerated growth conditions makes management difficult and results in lower yield. Genetic variability for all characters mentioned above have been reported which when combined should lead to identification of superior genotypes (Mann 1985).

In areas where receding soil moisture forces early seeding, wheat must germinate and tiller under high temperature conditions. Most wheats have reduced tillering and small spikes under these conditions. Good crop establishment and high early plant populations are important to preserve soil moisture and keep soil temperatures low. Genotypes with enhanced early growth (rapid germination and superior early vigor), resulting in greater ground cover, have always demonstrated better adaptation, and late germinating slow establishing lines never catch up.

Tolerance to late heat is important, not only for the nontraditional areas, but also for the traditional areas where hot winds during the grain filling stage result in smaller and shriveled kernels. Tolerance appears enhanced if the leaves remain green and active long enough to produce the required assimilates. Selection of Marcos Juarez INTA in Argentina, Paraguay, and Tunisia—where hot winds at the harvest time are common—probably indicates the ability of this variety to produce good grains under such adverse conditions.

Under hot environments, general earliness appears to serve as an escape mechanism from heat, diseases, or water shortages. Material tested in the 22nd

Table 2. Grain yield in kg/mm of moisture of advanced lines compared to dryland wheats Galvez 87 and C306 under increasing levels of drought stress.

Variety or line	Grain yield (kg/mm of moisture)				
	Drought stress level				
	No stress 1	2	3	4	High stress 5
Cruz Alta INTA	9.79	10.32	13.00	13.32	13.06
Genaro 81	13.45	15.08	17.59	17.16	14.80
Opata 85	14.27	13.36	16.46	17.22	14.95
Kauz'S'[a]	15.45	15.68	7.06	19.24	15.48
Vee 8/4/Vee'S'/3/ KLTO/PAT19//MO/JUP	14.97	14.69	18.09	19.79	17.40
F60314.76/4/CNO67/ 7C//KAL/BB/3/PCI'S' /5/CNO79[a]	11.15	11.58	17.56	20.18	19.57
Seri 82	14.41	15.11	17.73	22.41	20.83
Tyrant'S'[a]	15.00	15.51	18.32	22.55	21.91
Galvez 87	13.33	14.88	15.56	17.02	17.99
C306	8.77	12.43	14.92	17.49	17.88

[a] Superior under drought stress during Yaqui 1987-88.
Source: K. Sayre, pers. comm.

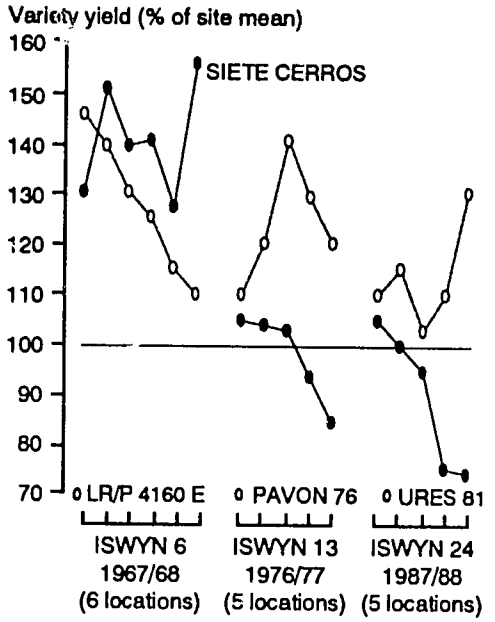

Figure 5. Yield of the respective top yielding entry compared to the yield of Siete Cerros 66 in drought stressed conditions of ISWYNs 6, 13, and 24.

and 23rd ISWYNs showed negative and often significant correlations between yield and days to heading as well as days to maturity in all locations classified as warm or tropical except one. Variety means over all locations also show highly significant coefficients of -0.61 and -0.39 for yield and heading days and -0.60 and -0.62 for yield and maturity in the 22nd and 23rd ISWYNs, respectively.

Other agronomic characters used to select in the warmer areas are: higher spike number and spike fertility (more grains/spikelet), longer leaf duration after anthesis and plump or at least nonshriveled kernels. Sudan and Brazil have released high tillering varieties such as Anza, Condor, and Kea, which have a small spike size but produce high yield. On the other hand, thousand grain weight is still an important yield factor in the subcontinent (Sonalika, UP262, Punjab 81, IP4). In Southeast Asia, grains per head is most often the yield component with the closest association with yield (Mann and Siripongse 1990).

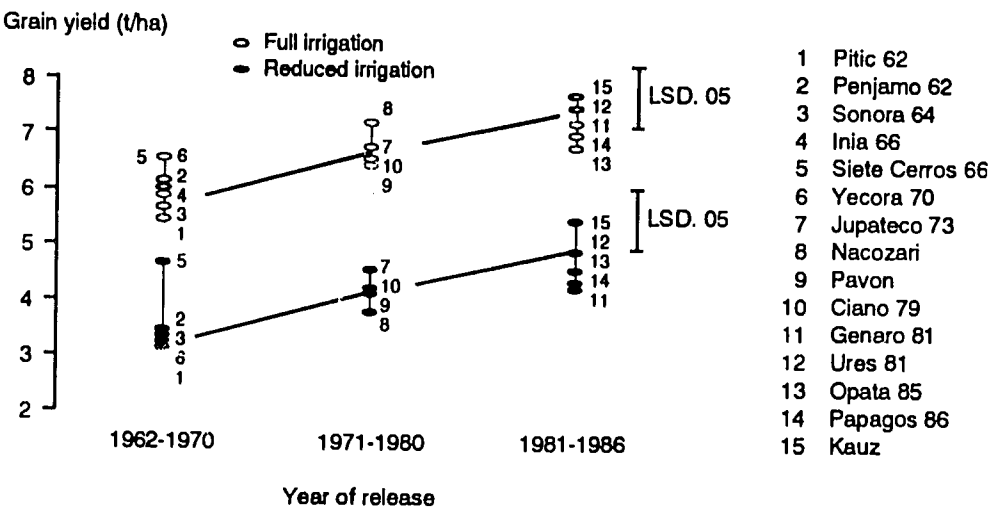

Figure 6. Yield of commercially grown semidwarf cultivars released during the 1962-86 period under full and reduced irrigation at CIANO, Cd. Obregon, Mexico. Source: Pfeiffer (1988).

Extending the early vegetative period by the utilization of vernalization and photoperiod genes has also been tried. While spring parents such as Cajeme 71 (Bluebird), Soltane (Marcos Juarez INTA), Gabo, and Pitic 62, known to have a differential response to vernalization (Fischer 1985) have resulted in several progenies adapted to the warm areas, the photoperiod genes have in general resulted in very late materials in the segregating populations.

At present, Chinese germplasm known for rapid grain filling is being utilized in crosses with new lines of intermediate spike size such as Kauz, Veery/Myna, and Myna/Vulture. These intermediate cycle lines have shown excellent yield potential in several South American countries, thus confirming the earlier assertion that prolonging the wheat cycle as far as possible in a warm environment may lead to increased yield. The stability analysis of the newer germplasm included in the 24th ISWYN at warm locations demonstrates a significant advantage over the older materials (Figure 8).

Aluminum toxicity and phosphorus uptake efficiency in acid soils—One of the major limiting factors to yield in the warm environments is soil acidity and related aluminum toxicity. Acid soils occupy approximately 1 billion hectares of the tropics and subtropics (Clark 1982). In terms of potential arable land, this represents nearly half of the total rainfed areas of Brazil, the Andes, China, Southeast Asia, the Himalayas, and Central and Southern Africa.

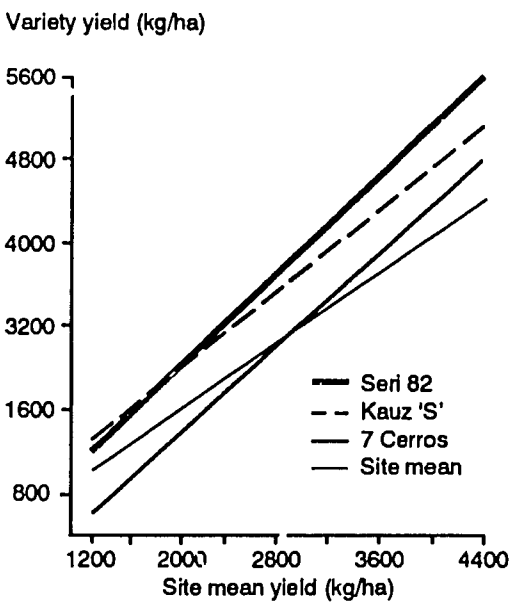

Figure 7. Yield stability of Seri 82 and Kauz'S' in comparision with Siete Cerros and the site mean at nine drought-stressed locations of ISWYN 24.

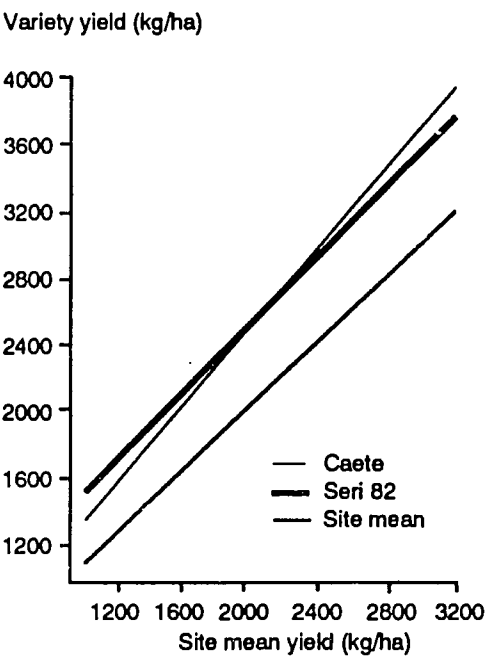

Figure 8. Yield stability of Seri 82 and Caete in comparison with the site mean at eight heat-stressed locations in ISWYN 24.

Genetic variability for resistance to toxic levels of aluminum (Al) and manganese (Mn) and for enhanced phosphorus (P) uptake efficiency has been observed and utilized in wheat. The collaborative shuttle breeding program started in 1974 between Brazilian Institutions and CIMMYT has led to the development of new aluminum tolerant, high yielding varieties (Kohli and Rajaram 1988). Brazil has released 51 Al-tolerant and 23 Al-susceptible varieties during the 1984-89 period (Table 3). Interestingly, while a majority of the varieties for the acid soils were derived from the local crosses, almost one-third are the result of the Brazil-CIMMYT shuttle program. On the other hand, three-fourths of the varieties released for the aluminum-free soils are direct introductions from CIMMYT germplasm. Compared with IAC 5-Maringá, a local high yielding variety, the new varieties are superior from 9 to 27%, depending on the region (Table 4).

Phosphorus uptake efficiency and resistance to Mn toxicity are other problems with acid soils. The ability of Brazilian varieties, such as BH1146, PG1, and Toropi, to extract P from soils with low P-availability is well known. Among the newer cultivars, Alondra seems to present the same character, although it is not tolerant to aluminum toxicity. Alondra, derived from the cross D6301/Nainari 60//Weique-Red Mace/3/Ciano*2/Chris (CM 11683), has played an important role in the breeding of high yielding varieties with Al tolerance. On the other hand, not all varieties, for example CNT 8, carrying tolerance to Al are efficient in P uptake (Camargo 1985).

Tolerance to Al does not mean tolerance to Mn as well. For example, wheat variety BH1146, known for high Al tolerance, is susceptible to Mn toxicity while the reverse is true for Siete Cerros (Camargo 1983). He demonstrated that tolerance to Mn toxicity is under genetic control and suggested the possibility of its transfer to Mn-susceptible germplasm. However, due to the patchy nature of the Mn problem, little progress has been made to include this character on the list of breeding objectives for improvement.

Breeding for disease resistance

The warm, humid environments present the greatest challenge to wheat production. In addition to acceptable agronomic adaptation and yield potential,

Table 3. Effects of shuttle breeding on the development of wheat varieties in Brazil, 1984-1989.

Breeding results	Aluminum soils	Nonaluminum soils
Varieties released	51	23
Varieties from Brazilian crosses	44	4
Varieties from CIMMYT crosses	7	19
Varieties derived from all Brazilian selections	35	6
Varieties derived from one or more CIMMYT selections	16	17[a]

[a] Direct introductions from CIMMYT.

germplasm must possess resistance to several endemic diseases. The advances in the incorporation of resistance to leaf and stem rusts and powdery mildew have been significant in the traditional areas and can be utilized. However, breeding for resistance to nontraditional diseases such as spot blotch and head scab has been slow and of major concern.

Spot blotch—Spot blotch of wheat caused by the fungus *Cochliobolus sativus* Ito et Kurib (syn *Helminthosporium sativum* P.K. and B) is probably the most widely distributed and serious disease in the warm and humid environments. Severe epidemics of spot blotch frequently occur in India, Bangladesh, the Philippines, Bolivia, Brazil, Paraguay, and Zambia. Another species, *Helminthosporium tritici repentis*, found chiefly in the traditional cooler climates is also observed to be increasing in the warmer areas where its spread is related to the increase in zero tillage.

Helminthosporium resistance breeding is a relatively new endeavor. Although CIMMYT has been screening germplasm in Poza Rica, Mexico, since the early 1970s, spot blotch has become a breeding priority only since 1981. Varieties from Brazil, the Yangtze River Basin of China, and southeastern USA (including varieties such as Horizon, Hadden, BH 1146, CNT 8, Suzhoe 8, and Yang Mai 6) have served as sources of resistance. At CIMMYT, spot blotch resistance from *Agropyron distichum*, *A. curvifolium*, and *Elymus giganteus* is also being transferred to wheat (M. Kazi, pers. comm.).

Through the international nurseries, it has been possible to identify key testing sites for spot blotch such as Los Baños, Philippines; Jessore, Bangladesh; Mbala, Zambia; Poza Rica, Mexico; Santa Cruz, Bolivia; and Londrina, Brazil.

Table 4. Performance of new aluminum tolerant semidwarf wheats in the warmer regions of Paraná, Brazil, 1987-1989.

Variety	Year Released	Yield as percent of the average of 3 top checks			
		Region A[a]		Region B+C[a]	
BR 23	1988	115	(9)[b]	108	(29)
OCEPAR 15	1989	115	(13)	107	(26)
OCEPAR 20	1990	106	(16)	111	(26)
BR 34	1990	117	(16)	118	(25)
BR 35	1990	116	(16)	124	(26)
Mirim	1990	106	(15)	106	(25)
Maringá	1972	91	(62)	97	(95)
BR 14	1985	93	(14)	91	(16)

[a] Region A = 22°30' to 24°30'S latitude, 49°30' to 54°W longitude, below 700 masl;
Region B = 23°30' to 25°30'S latitude, 53°15' to 54°30'W longitude, below 500 masl;
Region C = 23°45' to 26°15'S latitude, 51° to 54°W longitude, 500-800 masl.

[b] Figures in parentheses indicate number of yield trials.

Source: Brazilian Central South Official Yield Trials, 1987-1989.

Genetic variability for spot blotch has been identified (Table 5). However, instability in the degree of resistance at different geographical conditions has been noted. Multilocation testing done in Bolivia compared 11 varieties for mean spot blotch infection at four locations (Table 6). Results indicate that mean spot blotch infection levels in the susceptible varieties were higher as a group than others, but not statistically significant. Similarly, the analysis was unable to pinpoint the differences for spot blotch infection among resistant and moderately resistant cultivars observed under field conditions. Lack of a high degree of resistance and knowledge of its genetics has hampered the progress in the breeding programs. While this information is being developed, the alternative approach of pyramiding genes from different sources is being followed (Rajaram 1988).

Several advanced lines with moderate levels of spot blotch resistance combined with high yield have been identified by the CIMMYT breeding program. Some of the materials released recently include: Kea, Opata, and AU/UP301//GLL/SX. Additional germplasm, such as Kauz'S', Milan'S', and Chilero'S', are in the advanced stages of testing in various countries.

Besides shuttle breeding and multilocation testing to increase the level of spot blotch resistance in bread wheat, several breeding programs are also backcrossing and utilizing male sterility to develop recurrent populations.

In 1987, a German grant provided funds for the initiation of a network devoted to basic and strategic research on helminthosporium epidemiology, genetics of resistance, race analyses, and selection

Table 5. *Helminthosporium*-tolerant germplasm, Brazil 1989.

Variety/ Line	Area under the disease progress curve			
	Londrina	Palotina	Sta. Teresa	Average
Mitacore[a]	1957	1673	1170	1600
CNT 8[b]	188	435	483	369
Veery'S' (IA7956)	563	701	620	628
KVZ/K4500	581	550	585	572
BR 8	671	353	539	521
MON'S'/MN72131	450	250	650	450
NAD//TMP/CC12406/3/ BJY/4/TIF	450	288	480	406
BH1146*3/ALD	375	668	625	556
CEP 14	150	231	680	354

[a] Susceptible check.
[b] Resistant check.
Source: Y.R. Mehta, IAPAR, Brazil.

through toxins. This cooperative project, which involves several institutions and CIMMYT, supplements the UNDP-sponsored research.

Fusarium head blight—Fusarium head blight (FHB) or scab of wheat caused by *Gibberella zeae* (SCHW) Petch (*Fusarium graminearum* SCHW.) is another major limiting factor to yield, especially in areas having mild winters and warm, wet springs. These conditions frequently occur in East Asia, Australia, eastern and western Europe, North America, and the Southern Cone of South America (Luzzardi 1985, Luzzardi and Pierobom 1989).

High variability within *Fusarium* has limited the understanding of the nature of resistance to the fungus. The resistance is divided into two phenomena:

- Resistance to initial infection, and
- Resistance to spread within the spike.

The sources of field resistance identified so far are:

- China: Sumai 3, Nanjing 7840, Suzhoe 6, Wuhan 3, and Shanghai 5.
- Japan: Abura, Noboeka Bozu, Nyu Bay, Shinshunaga, and Tokai 66.
- Argentina: Klein Atlas and Tezanos Pintos Precoz.
- Brazil: Eucruzilhada, Toropi, PAT 19, Pel 73081, Pel 73087, Pel 73151, and Pel 74182.

The methodology of selection and evaluation of these genotypes has principally been based on artificial inoculations under controlled conditions. However, favorable greenhouse conditions and repeated inoculations are too strong to allow selection of genotypes with moderate levels of resistance. Information concerning the genetics of resistance in the sources mentioned above and the relationships between genotypes from different geographical regions is nonexistent. In addition, the difficulties associated with field screening of segregating populations have reduced the pace of advances in the scab breeding program.

Table 6. Least significant difference pairwise comparisons among 11 wheat varieties/lines for spot blotch resistance. CIAT, Santa Cruz, Bolivia, 1989.

Variety/ Line	Mean spot blotch[a]	Homogenous groups			
Pai Comomoci	98.00	I			
Mitacore	94.50	I			
Myna/Vul'S'	91.50	I			
Chilero'S'	39.00		I		
F3.71/Trm	64.00		I	I	
PF 79707	63.50		I	I	
Opata	61.00		I	I	I
PF 7339	59.75		I	I	I
Sara 82	54.75			I	I
Jar'S'/Klat	53.75			I	I
Milan'S'	48.25				I

[a] Expressed as percent of the most susceptible check.
T. value = 2.042; S.E. = 6.8044.

Early Brazilian work on FHB using Japanese sources of resistance and artificial inoculation have led to the development of some new lines with a better degree of resistance (Sartori 1989). CIMMYT's efforts to screen advanced materials internationally not only proved the superiority of the Chinese germplasm, but also helped to identify high yielding lines with moderate tolerance to FHB (Table 7). The average scab percentage, adjusted for days to heading and height, was measured as the deviation from the regression line of infection in the units of the standard error (Van Beuningen and Kohli 1990). While the Chinese germplasm such as Shanghai 3 and Nanjing 7840 were more than two units below the regression line, indicating a very high degree of genetic resistance, several advanced lines from the CIMMYT program were a unit or less under the regression line, which indicates a moderate level of resistance. The susceptible checks (e.g., Thornbird) were a unit or more above the line.

An intensive shuttle breeding program, initiated to transfer FHB resistance to high yielding germplasm, utilizes screening conditions of Mexico, China, and Paraguay. Although germplasm of this cooperative program is still in the initial stages of development, several advanced line collections and segregating populations have already been distributed. In both China and Mexico, additional sources of FHB resistance are being transferred from alien species such as *Agropyron*, *Elymus*, and *Haynaldia* to wheat by CIMMYT's wide crosses program. Chinese scientists are using the dominant male sterile variety Taigu to develop recombinant populations.

The loss of crop quality or the amount of toxin present in the grain does not correlate well with the visual FHB symptoms under field or controlled conditions. Experimental inoculation and chemical analysis for the amount of deoxynivalenol (DON) and ergosterol can provide an alternative measure of FHB resistance (Miller et al. 1985).

Table 7. Fusarium head blight evaluation of selected germplasm in 1st, 2nd, and 3rd SRSNs, 1987-1989.

SRSN Year	No. of Locations	Variety/line	Scab %	Dev. From Reg. Line[a]	Average Resistance
1987	11	Shanghai 3	12	-2.10	R
		IAS20/H567-71//5*IAS20	13	-1.04	MR
		MRNG/BUC'S'//BLO'S'/PSN	32	-0.87	MR
		Bobwhite'S'	32	-0.64	MR
		CEP7593/OC73 1070	56	1.76	S
		Thornbird'S'	38	1.36	S
1988	4	Ning 7840	4	-2.70	R
		2109.36/VEE'S'/4/WRM...	17	-1.12	MR
		JUP/2P//COC/3/PVN	23	-0.28	MS
		793.3402	44	1.99	S
1989	11	Wuhan 3	8	-1.52	R
		F3.71/TRM//3383.20	15	-0.71	MR
		Wydah	20	-0.31	MS
		PF7619/DOVE'S'//CEP7670	39	2.89	S

[a] Deviation from the regression line expressed in units of standard error.

Early screening done on carefully selected progenitors allows the combining of known sources of resistance. The trichotecene tolerance test can be used for intermediate evaluation. Wang and Miller (1988) used pure DON and acetyldeoxynivalenol on coleoptile tissue, a potential method to screen segregating populations. Plant and callus tissue screening of FHB using toxins, if successful, may allow a much wider evaluation of resistance to this pathogen.

Resistance to other diseases and insect pests—A recent survey conducted by the authors indicated that resistance to rusts, especially leaf rust, was still the top priority among breeders. Rajaram et al. (1988) believe that breeding for rust resistance should be based on durable factors (resistance over a long time span) in combination with major genes imparting high degrees of specific resistance, as well as genes slowing the rate of rust development. A large number of new lines carrying various combinations of these are already available to the breeding programs in the warmer areas.

Other wheat diseases of concern in the warmer areas include powdery mildew, septoria glume blotch, bacterial stripe and leaf blights, and various virus diseases, primarily barley yellow dwarf virus, soilborne mosaic virus, and recently rice (wheat) blast. Among the root diseases, helminthosporium crown rot and sclerotium wilt are the most important. With the exception of powdery mildew, very little effort has been made so far to breed for resistance to these diseases. In addition to sketchy information on their importance, lack of knowledge regarding pathogen variability, known sources of resistance, and adequate screening methods impede the development of resistant germplasm.

An alarming increase of rice (wheat) blast on wheat in Brazil (Igarashi 1988, 1991) may be foreboding for the large rice-wheat rotation areas of the world. However, incorporation of rice stubble and wheat seeding during recommended periods appear to reduce significantly the impact of the disease. Similar agronomic management of other diseases, especially root diseases, needs to be explored before deciding on a breeding program.

Breeders consider a number of insect pests to be important, including aphids and various species of stem borers, army worms, cutworms, wireworms, and white grubs. However, there has been very little or no effort to investigate the available genetic variability and develop screening techniques.

United States Department of Agriculture/ Oklahoma State University research has made advances in identifying and transferring green bug resistance (Burton et al. 1991). The Brazilian Agricultural Research Enterprise (EMBRAPA) has been able to transfer green bug resistance from Amigo and Largo into high yielding germplasm such as Jupateco 73 (O.S. Rosa, pers. comm.). Researchers at the International Center for Agricultural Research in the Dry Areas (ICARDA) in Syria are screening some Amigo-derived lines in the Middle East and Africa. Considering the widespread nature of the problem, a coordinated international effort will accelerate the development and screening of germplasm.

What Needs to be Done in The Future

Yield potential and stability

In a recent survey of 26 national programs in the nontraditional, warmer areas, all but one put the highest priority on increasing yield potential and stability in the warmer regions.

Based on the stability parameters identified through international testing, it is obvious that outstanding germplasm needs to be recycled. However, some basic studies on the contribution of various plant characteristics are necessary first. Higher biomass production, tiller survival, and distribution between vegetative and reproductive phases also need further exploration—perhaps through spring x winter crosses. Meanwhile, the transfer of multiple disease resistance to the existing high yielding germplasm—with some tolerance to abiotic stresses—remains a top priority.

Exploitation of genetic variability
In addition to the utilization of germplasm selected from the warmer regions, screening of the world wheat collection and alien species for specific characters or their combinations is urgently needed. At the same time, potential of new technologies in transferring important characters to wheat or within wheat species need to assessed.

Genetics of important characters
Although the international nursery network has served to identify outstanding germplasm and the existence of variability for a specific character or group of characters, it does not provide information on the genetic control involved. The assumption that genetic materials coming from different geographical regions carry different sets of genes for a particular character, as in the case of rust resistance, cannot be taken for granted. Therefore, there is an urgent need to expand knowledge regarding the genetic constitution of key materials and the genetic base of important characteristics. The role of new tools such as RFLPs in obtaining such knowledge needs to be explored.

Accelerating the pace of character screening
Field screening of different characters at key sites has produced excellent results in the past. In the future, the use of new screening techniques, such as those utilizing disease-related toxins and abiotic stress-related chemicals, may accelerate the selection process. Other techniques worth exploring include FHB screening using crude toxins or ergosterol, which is being done in China and Canada, and drought tolerance screening using Carbon-13 discrimination (Acevedo and Cecarelli 1989).

More cooperative ventures
The success story of the cooperative efforts between Brazilian institutions and CIMMYT in developing high yielding, aluminum-tolerant germplasm is well known. Similar cooperative efforts are needed to work with other traits such as drought and heat tolerance and spot blotch and scab resistance. Although these characters may be governed by complex genetic systems (in comparison to the relatively simple situation involving aluminum tolerance) in addition to needing sites of uniform screening pressure over a number of years, well defined progenitors in the crossing program and multilocation selection of germplasm are likely to produce results soon.

The commitment of interested national programs, donor agencies, and CIMMYT is critical to the development of superior wheat germplasm and varieties for the nontraditional warm areas.

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Resumen

Las tendencias recientes del consumo y la importación de trigo por los países en desarrollo en regiones cálidas causan seria preocupación y constituyen una razón fundamental para que esos países aumenten su producción de trigo. Desde comienzos del decenio de los 70, se han seleccionado variedades de los viveros internacionales y se las ha lanzado para la producción comercial en las regiones cálidas. Durante el período del proyecto auspiciado por el Programa de las Naciones Unidas para el Desarrollo (PNUD), se ha identificado y distribuido germoplasma mejorado, adaptado a las regiones cálidas, con un rendimiento un 10-20% superior al de Anza. Aún es necesario combinar más el germoplasma superior para obtener otras características importantes, como la ya identificada resistencia a factores bióticos y abióticos desfavorables, con el fin de generar variedades de adaptación amplia. Se han logrado éxitos importantes en la obtención de variedades para suelos ácidos con toxicidad por el aluminio y provistas de una base más amplia de resistencia a las royas. Sin embargo, es preciso mejorar más la resistencia a la sequía, el calor, la mancha foliar y la roña. Si bien el mayor potencial de rendimiento y la estabilidad, combinados con la resistencia a las enfermedades, serían la meta inmediata para los futuros programas de mejoramiento de trigo, la explotación de la variabilidad genética adicional, el conocimiento de las bases genéticas de características claves y el empleo de técnicas rápidas de selección en las actividades conjuntas dentro de los programas nacionales y entre éstos y el CIMMYT, serán críticos para la generación de germoplasma.

New Technologies and their Application to Wheat Breeding in Warmer Areas

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Abstract

Several of the new technologies successfully applied to dicotyledonous species have proven more difficult when attempted with cereals. Limited improvements have been made in technologies, such as haploidization and cell and tissue cultures, but genotype specificity and/or yield of regenerates are still problems. Protoplast regeneration has not been reported for wheat and current emphasis in transformation research involves methods that do not require regeneration such as biolistics, microinjection, and agrobacteria. Transformation holds much promise; however, the time frame for implementation in wheat could be substantial. The most promising technology that is likely to be applied to wheat improvement in the next 5 years is the use of restriction fragment length polymorphism (RFLP) linkage maps and the resulting markers. RFLP markers, closely linked to a desirable gene, will greatly facilitate the movement of these genes among varieties, expedite the introgression of genes from alien germplasm, aid in the elucidation of gene expression and analysis of polygenic traits, and determine genetic relationships among varieties and species. Since most of the problems that breeders face involve polygenic traits with low heritability, it is critical that new technologies address this problem. Computerization and improved statistical analyses are already having an impact and are likely to become standard components. Probably the most difficult problems of implementing the newer technologies are cost, government regulations, and public perception of the safety of genetically engineered food crops. Many of these technologies are still in the development stage. To be useful to breeders, they must become routine, inexpensive, and very reliable.

Introduction

This paper focuses on new breeding technologies and strategies and the likelihood of their use in the near future for improving wheat. I will use a few examples of problems in warmer wheat growing regions, however, the strategies may be equally applied to all wheat regions since trait characteristics largely determine the breeding strategy (e.g., number of controlling loci, heritability, cost, and difficulty of evaluation).

Breeding Strategies, Methods, and Technologies

Breeding strategies are combinations of methods (e.g., pedigree, bulk, SSD) and techniques (e.g., pathogen inoculation, plot planting, bread baking). The use of new technologies, such as haploidization, often results in new breeding strategies. Similarly, new strategies often place renewed emphasis on old methods. For example, the use of DNA markers to select specific genes as well as individuals with a high percentage of the recurrent parent genome greatly enhances the value of the backcross breeding method. New breeding methods are rare, while new or improved technologies occur frequently. Changes in cultural practices and trait value also cause breeders to alter their strategies. The science of plant breeding involves the integration of techniques and methods for optimization of breeding strategies to achieve specific breeding goals.

What are the newer technologies? There are many new technologies as well as older ones that have been greatly improved. The following is a partial list of those more commonly recognized.

Haploidization—This is the process of generating sporophytic genotypes possessing the gametic number of chromosomes. Various methods have been used including *Hordeum bulbosum* and maize as special pollinators and anther culture. Haploids can be used to speed the production of inbred lines.

Tissue culture—This is the *in vitro* cu re of cells as calli. Tissue culture can be used to regenerate plants that may exhibit somaclonal variation for a wide range of traits (see review by Liang and McHughen 1987). Cell colonies can be grown on selective media and surviving colonies then transferred to media that promotes regeneration. Embryogenic calli also can be used for transformation via biolistics or microinjection. *In vitro* evaluation for resistance to certain diseases may facilitate evaluation and increase heritability, e.g., scab (Miedaner 1988), septoria (Karjalainen 1984).

Protoplast culture—This refers to single-cell culture in a liquid medium. Protoplasts are required for transformation using electroporation or polyethylene glycol. Somatic cell hybridization also requires totipotent protoplasts.

Transformation—This process introduces foreign DNA into a target organism's genome. Various methods have been developed including the particle gun, agrobacterium, electroporation, microinjection, and pollen tube uptake. For a review, see Potrykus (1990).

RFLP mapping—This construction of a saturated linkage map consists of DNA clones. By using different restriction enzymes, polymorphism can be detected between various genotypes. Clones that are closely linked to genes of economic importance can be used as selectable markers in segregating generations.

In situ hybridization—This cytological technique allows the visualization of highly repeated sequences on metaphase chromosomes. A radio-labeled or biotin-labeled probe is incubated with a preparation of dividing cells and allowed to hybridize to complementary sequences. After washing away the unhybridized probe, the location of the probed regions is inferred from autoradiography and/or light microscopy (e.g., see Lapitan et al. 1987).

Wide hybridization—This involves interspecific and intergeneric crosses that can be used to introduce novel genes for traits such as disease resistance. This is not a new approach, but one that has improved substantially in recent years through better hybridization and embryo rescue. A simple "squash dot" assay using a rye repeated DNA probe can be used to identify wheat lines having the 1B/1R translocation or other rye segments (Hutchinson et al. 1985). Introgression of alien germplasm is likely to receive much more emphasis in the near future.

Chromosome banding—Known as C- and N-banding, this has greatly enhanced chromosome identification in wheat (Gill 1987).

Improved gametocides—Improved gametocides for production of wheat hybrids are likely within the next 5 to 8 years. Hybrid wheat cultivars produced using cytoplasmic male sterility have been in commercial use for several years; however, the high cost of inbred development and seed production has been a major factor limiting their use. The future discovery of DNA markers linked

to restorer genes could greatly facilitate inbred development for cyto-sterile produced hybrids.

Infrared spectrometry—This research has made substantial progress relating specific wavelengths to quality factors. The technology is already being used in major laboratories to supplement conventional baking quality analyses.

Computerization—Computers have brought many benefits to plant breeding. Probably the most important uses are record keeping, fieldbook and label generation, and data summary.

Improved statistical analysis—Methods are still being developed such as the AMMI (Additive Main Effects and Multiplicative Interaction) analysis that facilitates the understanding of genotype by environment interaction (Gauch and Zobel 1988). A thorough understanding of patterns of genotype by environment interaction becomes more important as genotypes are more precisely defined and as testing methods improve.

Newer wheat breeding strategies

Doubled haploid breeding—This has aroused considerable interest in recent years as methods of generating haploids become more efficient. Baenziger et al. (1984) recently reviewed applications of doubled haploid breeding. Primary advantages of this method include rapid line stabilization and time savings during inbreeding. While a few barley cultivars have originated as doubled haploids, apparently, no wheat varieties have been developed using this method. Genotype specificity and very low regeneration frequencies are still major problems with anther culture and *H. bulbosum* derived haploids. There have been no reports of genotype specificity for the maize pollinator method and maize pollen is insensitive to the Kr loci (O'Donoughue and Bennett 1988). Frequency of recovery of bread wheat haploids has been approximately 2% with maize pollen (A. Mujeeb-Kazi, pers. comm.). If the percent recovery of haploids can be increased, this method is likely to receive much more attention in the near future.

Recurrent selection—This has been the subject of several studies (Abdalla et al. 1989, Beek 1986, Löffler et al. 1983). However, it is rarely used by wheat breeders for cultivar development. Probably, the primary reason breeders reject recurrent selection methods is the time required to realize a return from the investment. It is somewhat labor-intensive and potential results are uncertain. When new sources of disease resistance or other traits become available, they are difficult to incorporate into the population and once introduced often remain at low frequency. It is unknown if there are beneficial effects of several generations of intermating and genetic recombination or if there are elite linkage blocks that should be preserved.

While doubled haploidy could speed up cycles and increase heritability, before using doubled haploid recurrent selection one should consider:

- The relative length of the recurrent selection cycle.
- How many fertile doubled haploids can be produced.
- The type of gene action and the importance of the environment (Scowcroft 1978).

We are currently evaluating several recurrent selection populations developed using the dominant male-sterile gene (Sorrells and Fritz 1982). While improved populations are likely to be excellent sources of new lines, it is questionable whether the cost and time are justified.

Molecular genetics—Research in this area has resulted in the recent development of new tools such as restriction enzymes for genetic analysis. This has opened up several new research areas that may be of benefit to wheat breeders in the foreseeable future. Using DNA markers, cultivars can be "fingerprinted" to verify their identity, relationships among genotypes can be assessed, and often the parentage can be determined. DNA clones can be used to develop RFLP linkage maps that can be used to locate genes of importance, assess their effect on the phenotype, and then follow them in segregating populations. More recently, it has been possible to identify loci affecting quantitative traits (QTL) (Paterson et al. 1988). Once the QTL is located near two linked DNA markers, the locus can be evaluated for the proportion of the variation that is controlled and if there are pleiotropic or epistatic effects.

A wheat RFLP linkage map could be used for wheat variety improvement in several ways:

- RFLPs can be used to identify and combine desirable genes from different varieties.
- Selection against undesirable linked genes and gene interactions can be practiced.
- RFLP markers expedite the introgression of novel genes from related species.
- Genetic diversity in the primary gene pool can be accurately assessed.
- Positive identification of cultivars and germplasm is possible with relatively few probes.

In the future, high density RFLP maps may facilitate the cloning of genes whose products are unknown, such as genes for disease resistance and stress tolerance.

As markers for use in plant breeding programs, RFLPs differ from morphological markers in several important ways (Tanksley et al. 1988):

- Alleles for morphological markers normally exhibit dominance or recessiveness. RFLP markers are screened at the DNA level, and thus, exhibit co-dominant segregation.
- The level of allelic variation for RFLP markers is much greater than that for morphological markers (Helentjaris et al. 1985).
- RFLP markers are believed to be phenotype-neutral; whereas, morphological markers frequently have major undesirable phenotypic effects.
- Morphological markers often interact epistatically, thus limiting the number that can be scored in a segregating population. RFLP markers are apparently free of epistatic interactions and the number that can be scored in a population is virtually unlimited.
- DNA can be extracted from virtually any tissue. Protein markers are limited by the availability of rapid stain techniques and the genes coding for the proteins must be expressed in assayed tissues.

Alien species have been the source of many disease resistance genes in wheat including stem rust, leaf rust, stripe (yellow) rust, and powdery mildew (Knott and Dvorák, 1976). RFLP markers are especially well suited to tagging genes from alien species because regions flanking the target gene are very likely to be polymorphic to cultivated varieties. This was well illustrated by the RFLP map data from group 7 reported by Chao et al. (1989). Their data showed that a large chromosome segment on 7D originated from *Aegilops ventricosa* that

resulted in very high polymorphism in a Hobbit x VPM1 cross. Alien genes are often incorporated into new cultivars by backcrossing or some modification of the backcross method.

The use of RFLP linkage maps has the potential to increase dramatically the efficiency of backcross breeding and overcome major limitations of the method. First, the segregating population can be screened at the seedling stage for RFLP markers and desirable individuals can be identified prior to hybridization with the recurrent parent. RFLP markers also facilitate selection of both qualitative and quantitative trait loci. Segments from the nonrecurrent parent can be monitored and individuals containing the highest proportion of the recurrent parent genome can be used in the next backcross. A high density RFLP map can be used to identify recombination events that occur very close to the desired gene segment. Even after 20 generations of conventional backcrossing, an average of 10 cM of the donor genome remains linked to the target segment, which is large enough to contain hundreds of genes (Young and Tanksley 1989). In contrast, RFLP-based selection can eliminate or significantly mitigate linkage drag.

In conventional backcrossing, there is no way to identify recombination events close to the gene of interest. With a high density RFLP map, there is a 95% chance that, in one generation of 300 individuals, there will be a crossover within 1 cM of the selected segment (Young and Tanksley 1988). Without RFLPs, more than 50 backcross generations would be required for 95% probability of obtaining a backcross individual with a crossover within 1 cM of a target gene segment. Because little additional effort is required to screen with multiple RFLP probes, one could consider adding many genes simultaneously to a variety. This power to rapidly and precisely modify the plant genotype should allow breeders to respond more quickly to market demands and unexpected environmental stresses and pathogen pressures.

Limitations of New Technologies Applied to Wheat

Crop improvement via transformation requires the availability of well characterized, cloned genes, a delivery system, expression in the target genotype, and transmission to sexual offspring. Transformation of wheat with genes from other species holds great potential and a few years ago, optimists were predicting early success. While much progress has been made, many problems have arisen especially in the areas of plant regeneration and field scale testing. To date, researchers have not reported a protoplast regeneration system for cultivated wheat. Even if a protocol for wheat is developed in the next few years, historically such systems have been somewhat genotype-specific.

Some transformation protocols require protoplasts; others do not. Potrykus (1990) has presented an excellent review of gene transfer potential for cereals. Cells must be competent for both transformation and regeneration. The wound response is one of the most effective triggers for converting cells to the competent state, but cereals have little or no wound response. One protocol being intensely studied is the use of microprojectiles to deliver DNA into meristematic regions or embryogenic callus. While *in vivo* expression of constructs has been obtained, incorporation into germ cell lines has not yet been successful (Wu, pers. comm.). There is some concern that cereal meristematic cells may not be transformation competent. Picard et al. (1988) reported transformation using the pollen tube vector system where pollen is treated with a solution containing the

plasmid and a selectable gene. Preliminary analysis of the F_2 generation suggested that incorporation into the genome had occurred, but this has not yet been confirmed. Although successful agro-infection of wheat seedlings using *Agrobacterium tumefaciens* has been reported, the viral DNA does not integrate, even if it reaches rare competent cells in the plant. There are reports of transformation of protoplasts in wheat or wheat relatives; however, their utility will require a regeneration protocol.

Before transformation can be attempted, clones of important genes must be available. Genes of interest for cloning include those conferring herbicide resistance, disease resistance, insect resistance, seed protein quality, transposable elements, and male sterility. More difficult, but potentially useful, genes might include those altering height, vernalization requirement, duration of developmental stages, salinity tolerance, grain dormancy, and drought tolerance. Another area of research is anti-sense RNAs and DNAs that work by suppressing gene expression. Gene suppression would be useful for removing anti-quality factors or for controlling genes that suppress useful disease resistance. The availability of cloned genes (patented or not) is likely to limit the utility of transformation technology for several years. In maize, transposable elements have been used to locate and isolate genes of interest (e.g., Federoff et al. 1984). Recently, Flavell et al. (1988) have reported two transposons, one of which was located in the *Glu-A1* gene of Chinese Spring. Thus, the same approach may become feasible in wheat in the next few years.

Wheat is also a challenge to geneticists wishing to construct an RFLP map and use gene tags. Cultivated wheat has a very large genome and a high percentage of repeated DNA. Arabidopsis has 0.07 pg of DNA, tomato 0.7 pg, and wheat 18 pg per haploid cell (Galbraith et al. 1983). This creates mapping problems because clones derived from wheat have a high probability of containing a repeated sequence. Also, a single fragment represents a much smaller fraction of the DNA on a hybridization filter, and consequently, the signal strength is much lower for species with a large genome. Single-copy clones (triplicated in wheat) are the most useful for RFLP mapping, but they are relatively rare (about 8%) (Chao et al. 1989). Thus, a major limitation to using DNA markers is that the specific marker that is linked to the gene of interest must be polymorphic for the particular pair of genotypes that the breeder is hybridizing.

Application of New Strategies to Wheat Improvement

Identification of genetic variation among cultivars and related species is facilitated using DNA markers. Within cultivated wheat, breeders can use DNA markers to detect and quantify genetic variation. This is important for parental selection in breeding programs because of the potential for predicting the agronomic performance of progeny from a cross (Souza 1988, Cowen and Frey 1987). Numerous studies have been conducted comparing genetic relationship to F_1 performance. For a review, see Virmani and Edwards (1983). A better characterization of the genetic resources available in our gene banks would allow breeders to develop logical sampling strategies for utilization of wild germplasm in wheat improvement (Marshall and Brown 1975). Testing could be restricted to those accessions that were both representative and at the same time genetically divergent. If the required genetic variation does not exist in the cultivated species, then more exotic technologies such as transformation might be explored.

Improvement of secondary traits is likely to receive more attention. As new wheat cultivars become more highly refined and it becomes more difficult to improve yield *per se*, emphasis is likely to shift to other traits amenable to manipulation using new technologies. Baking quality is a good example. Much progress has been made relating specific glutenin bands separated by polyacylamide gel electrophoresis to baking quality (Payne 1987). The use of certain glutenins to enhance end product quality could reduce cost of baking quality evaluation considerably. Resistances to many diseases are difficult to evaluate and a marker linked to a major resistance gene can be used by breeders indefinitely. Probably the greatest potential for the use of DNA markers is in the identification of positive alleles at different loci that can be combined in a single transgressive segregate for the trait. The use of selectable markers for a wide variety of economically important alleles is likely to increase the volume of this breeding activity.

The use of molecular markers for mapping in wheat is not a new idea. The RFLP for the nucleolar organizer, protein variation for glutenin and gliadin proteins, and a restorer gene for cytoplasmic sterility conditioned by *T. timopheevi* were used to map the genes for each trait (Snape et al. 1985). With appropriate probes for important traits, stringent culling selection in early generation seedlings should be possible. The value of this approach will be readily apparent in final stages of advanced testing.

Evaluation and screening operations are critical to the success of a breeding program. The most expensive and time consuming aspect of cultivar development is evaluation in regional yield trials. What can the newer technologies do to reduce the work load or improve efficiency at this stage? Obviously, rigorous screening for more traits in early generations will help to eliminate inferior genotypes before they reach yield trials. Technologies that promote a shift in breeding strategy toward backcross or modified backcross breeding may reduce yield trial testing requirements. Also, technologies that improve the accuracy of the trials (planting, harvesting, and computing equipment) or improve our ability to interpret the results (statistical treatments) also effectively reduce cost. Plant breeding requires evaluation of large numbers of genotypes and the newer technologies allow breeders to evaluate ever larger volumes of material more accurately. Molecular genetics is unlikely to change the way genotypes are evaluated because of the tremendous sophistication necessary to predict genotype performance in a single environment, not to mention the multiple environments encountered in commercial use.

An impressive statistical treatment has been published known as AMMI that partitions the treatment degrees of freedom into a pattern-rich model and a noise-rich residual that is discarded (Gauch and Zobel 1988). This has proven to be a very effective model with improved efficiencies comparable to 5 to 20 additional replicates. Gauch and Zobel (1990) have developed a recent version (MAMMI) that allows missing data.

Reduced generation time is becoming more important. Numerous papers have been published over the years describing methods of reducing generation time, usually for single-seed descent. Today, there is only one parameter more valuable than money—and that is time. The length of the generation time becomes especially important when backcrossing or when a new gene for resistance to a pathogen must be introduced into the breeding pool as rapidly as possible. Doubled haploid breeding can be effective since

homozygous lines are obtained from the F_1 generation; thus approximately 2 years can be saved by eliminating three or four generations.

Another approach is to increase the progress achieved in each generation toward a target genotype. Traditionally, breeders using the backcross method have selected for the trait of interest and for the recurrent parent phenotype to hasten progress. This can be accomplished more rapidly using DNA markers by selecting target genes from the source parent and at the same time selecting the recurrent parent chromosome segments in the rest of the genome. Using the backcross method and DNA markers, Young et al. (1989) estimated that, in a population of 200 tomatoes where there are three target gene segments being backcrossed, the number of backcross generations required can be reduced from more than 11 to only 3 by selecting individuals with the smallest target gene segment and the highest proportion of the recurrent parent genome

Problems in Warmer Areas

Among the most important disease problems in warm wheat growing regions are *Helminthosporium sativum*, head scab, leaf rust, loose smut, and the root rot complex. With the exception of race-specific rust resistance, these diseases are characterized by low heritability and polygenic inheritance, and they are very troublesome to evaluate. The more appropriate tools that are likely to be available to wheat breeders in the next 10 years to combat these problems are molecular markers, doubled haploid breeding, and wide hybridization methods. Probably the most dramatic changes will be in the application of molecular markers. This technology is already being used in tomato breeding for improving both qualitative and quantitative traits. To map a quantitative trait locus, several markers along the chromosome are required. By applying statistical tests with Mapmaker software (Lander and Botstein 1989), one can determine "likelihood intervals" (Paterson et al. 1988) for possible locations of QTLs. Using this approach, Paterson et al. (1988) have located several QTLs affecting tomato fruit weight, soluble solids concentration, and fruit pH so that adjacent DNA markers can be used as a proxy for the presence of the QTL. The genetic basis of transgressive segregation can be elucidated using genetic markers. For example, two wild relatives of tomato were known to have fruit pH similar to cultivated tomato, but using DNA markers to follow an individual locus, it was found that each species carries different alleles that increase or decrease pH relative to cultivated tomato. Thus, occasional progeny lack either the positive or negative alleles and are more extreme than either of the parents. Identification of rare transgressive segregates is fundamental to plant improvement. DNA markers will allow breeders to both create and identify transgressive segregates for important traits.

Increased use of computerization and infrared reflectance technology is likely as processors become more sensitive to milling and baking quality. *In vitro* screening techniques could be quite valuable if they were found to relate well to field reaction.

Concerns

The cost of implementing some of these newer technologies is currently very high and well beyond the reach of most breeding programs. However, material costs usually decline as companies scale up production. Also, researchers and companies gradually discover less expensive methods and sources. Cost estimates change rapidly for certain technologies. A recent estimate in our own lab put the cost of DNA marker technology at about US$0.60/genotype per

probe, which is comparable to a cost analysis by Beckmann and Soller (1983). One could analyze a population of 100 genotypes for 50 probes for about US$3000. Material costs for doubled haploid breeding, *in vitro* screening techniques, and wide hybridization are minimal, but labor costs are quite high because skilled technicians are usually required. Only breeding programs that are large enough to support specialized personnel can afford to maintain such positions.

Government regulations are proliferating as environmentalists expound the hazards of releasing genetically engineered organisms into the environment. While there are differing opinions regarding the release of genetically engineered organisms, increased regulation is likely, which slows development time and drives up costs. Only those technologies that avoid genetic modification of the wheat plant will avoid this potentially prohibitive cost. It is critical that regulations dealing with the commercialization of genetically engineered crops be internationally formulated and coordinated so as not to discriminate unnecessarily because of the particular biotechnology employed.

One of the most difficult problems with implementing certain technologies that is often overlooked is the public perception that genetically engineered plants may harm people or the environment in some way. There is little that scientists can do to alleviate this problem other than assist in educating the public as to the benefits of biotechnology and the safety precautions that scientists routinely employ.

Conclusions

This brief paper has tried to identify newer technologies and breeding strategies that are likely to be useful to breeders improving wheat for the warmer wheat growing areas. Many of the technologies mentioned are still in the development stage. To be useful to breeders, they must become routine, inexpensive, and very reliable. An obvious approach to using these technologies is to first select for traits of high priority and/or for highly heritable traits. At this point, much of the breeding material has been discarded and mostly elite materials remain, additional evaluation can be performed using more costly technologies.

Transformation holds much promise; however, the time frame for implementation in wheat could be substantial. There are many uncertainties related to gene expression, pleiotropic effects, government regulation, and public perception. The use of selectable markers has the highest probability of successful application to improving wheat for traits critical in warmer wheat growing areas. RFLP techniques will likely be integrated into existing plant breeding programs allowing breeders to access, transfer and combine genes quickly with precision not previously possible. For the near future, most of the applications of molecular genetics to wheat improvement will involve qualitative traits; however, technology for tagging loci controlling quantitative traits is close behind. In the foreseeable future, quantitative traits will be reduced to their Mendelian components, evaluated, and recombined to produce varieties with combinations of characters that were previously too difficult or time-consuming to produce.

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Resumen

Varias de las tecnologías nuevas aplicadas con éxito a las especies de dicotiledóneas han resultado más difíciles cuando se ha intentado utilizarlas con los cereales. Se han efectuado ciertos perfeccionamientos de las tecnologías, como la haploidización y los cultivos de tejidos y de células, pero siguen siendo un problema la especificidad de los genotipos y/o el rendimiento de los regenerados. No se ha informado que se haya logrado la regeneración de protoplastos en el trigo y el énfasis actual en la investigación de transformación implica el empleo de métodos que no requieren la regeneración, como la biolística, la microinyección y las agrobacterias. La transformación parece ofrecer grandes posibilidades; sin embargo, podría transcurrir mucho tiempo antes de que se use con el trigo. La tecnología más promisoria que probablemente se aplique en el mejoramiento del trigo en los próximos cinco años es el empleo de mapas de ligamientos de los polimorfismos por segmentos de longitud restringida (RFLP) y los marcadores resultantes. Los marcadores RFLP, estrechamente ligados a un gen conveniente, facilitarán mucho la transferencia de estos genes entre variedades, acelerarán la introducción de genes provenientes de germoplasma exógeno, contribuirán a la determinación de la expresión de los genes y al análisis de las características poligénicas y definirán las relaciones genéticas entre las variedades y las especies. Como la mayoría de los problemas que afrontan los fitomejoradores se relacionan con características poligénicas de escasa heredabilidad, es fundamental que las tecnologías nuevas aborden esta dificultad. La computarización y los análisis estadísticos perfeccionados ya están dando buenos resultados y probablemente se conviertan en componentes de uso común. Es posible que los mayores obstáculos para la aplicación de las tecnologías más nuevas sean el costo, las disposiciones gubernamentales y la percepción del público respecto a la seguridad de los cultivos obtenidos mediante la ingeniería genética. Muchas de estas tecnologías están aún en la etapa de desarrollo; para que sean útiles en la fitogenética, se deben convertir en instrumentos de uso ordinario, poco costosos y muy confiables.

The Status of Wheat Diseases and Disease Research in Warmer Areas

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Abstract

A questionnaire was sent to wheat researchers in the warmer areas of the developing world to determine the status of wheat diseases and research in these regions. Although this method lacks the desired precision, it permits a global estimate of wheat researchers' perceptions of disease effects and related information.

Data on disease importance are presented by temperature zones. Bipolaris sorokiniana *is confirmed as the most economically important foliar pathogen in all zones.* Puccinia recondita *and fusarium scab appear important in all zones and* Drechslera tritici-repentis *mainly in the coolest zone of the warmer areas. In the two hottest zones,* Sclerotium rolfsii *and* Fusarium *spp. are noted as the most damaging soilborne diseases and in the coolest area,* Fusarium *spp. and* Gaeumannomyces graminis *dominate.*

Appropriate quantitative yield loss data were not available, but chemical disease control trials showed significant actual and potential losses by the above diseases in these areas. Questions were asked about interactions of the main diseases with crop management, soil fertility, rotation crops, and cryptic diseases. In most cases, the answer was affirmative and observations are presented.

It is felt that the scarcity of research literature on diseases, even in national journals, is a true reflection of the situation. Objective surveys and loss quantification are needed to prioritize in-depth research efforts. Integrated control procedures appear to be the most logical in reducing losses. Based on the above research recommendations are made.

Introduction

Fungal diseases appear to cause the most important biotic stresses of wheat in the warmer areas. Previous international conferences (CIMMYT 1985, Klatt 1988) clearly emphasized the importance of fungal diseases as compared to other incitants. A review of the first meeting shows a strong emphasis for research on *Bipolaris sorokiniana* (Sacc.) Shoemaker (syn. *Helminthosporium sativum* P.K. and B.) the causal organism of spot blotch (CIMMYT 1985). Fusarium scab (principal incitant = *Fusarium graminearum* Schwabe) also was highlighted with lesser emphasis on foot rots and chemical control. At the second conference (Klatt 1988), the organizers stressed fungal diseases, but tried to balance the papers to represent what was empirically thought to be the most important diseases. Hence spot blotch and sclerotium foot rot (incitant = *Sclerotium rolfsii* Sacc.) received special mention.

The principal purpose of this paper is to ascertain the status of wheat diseases and research in the warmer areas. Several electronic literature searches indicated few articles in international journals. However, some publications in national journals as well as reports were available. When comprehensive survey data are not available in relation to disease status in large areas, other less precise methods may be used. Questionnaires are commonly used to obtain information, especially on disease occurrence and yield loss. These are an improvement over the

simple expert testimony statements that may be obtained (Teng 1981). Questionnaires are obviously inferior to ground or remote sensing surveys and experimentation. Nonetheless, questionnaire results can provide useful initial information on diseases and disease research status and, thus, provide a basis for establishing priorities. Questionnaires were sent to 77 selected scientists (primarily pathologists) in the warmer wheat areas of the world and about 35 usable ones were returned.

This paper, then, is primarily based on those questionnaire responses and attempts to update the situation with regard to wheat diseases and research rather than present an exhaustive review. We have also utilized articles, reports, and discussions with many of the scientists, as well as our own experiences, where appropriate.

Some Comments on Methodology

As noted, questionnaires have inherent limitations. The questions may contain biases of the writers and how the question is worded will affect the answer. Anomalous answers were obtained in some cases because of misinterpretation of the questions. For example, actual disease occurrence and importance were confused by some with potential dangers. In some cases, respondents made clear omissions of obvious diseases. Answers appeared most reliable when dealing with the evidently important diseases.

Finally, the analysis of these types of data can be done in several ways that are not truly subject to the rigors of statistical analysis. They will depend on the analyst's skills to bring the information together in a sensible, coherent, and reasonably unbiased manner. Nevertheless, they generally will contain some of the writer's prejudices.

The questionnaire responses, where appropriate, were divided into three environmental (climatic) zones based on mean temperatures of the coolest month of year, as modified from Fischer (1985). This is probably the most relevant and simple climatic parameter available that affects wheat adaptation. Similarly, climatic factors affecting wheat adaptation will also affect its pathogens. Another environmental factor of importance to disease will be the presence of free water in the form of rain or dew.

Table 1 shows the source of the questionnaire responses by environmental zones and, where available, information on the general climate during the wheat season. Table 2 presents the generally accepted scientific names of the wheat pathogens discussed in this paper. In some cases, various names are in common usage and synonymies are given.

Results

Research interests of questionnaire respondents

One can infer from Table 3 that foliar diseases are considered to be most important by the respondents since 70% of them work on these diseases. Rusts and soilborne diseases are also considered important. The types of controls being studied clearly are resistance- and chemical-based, with little to none in biological or crop management measures. The respondents are clearly mycology oriented in these areas with minimal effort being given to bacteriology, nematology, or virology.

Although one may conclude that bacterial, nematological, and virological problems are not important, this may not be so. These types of diseases may be of importance but may be presently unrecognized. Epidemiology appears to be considered important, but interestingly, etiology (study of disease causes) was not.

Table 1. Source of questionnaire responses by environmental zones.[a]

Country	Number of questionnaires received	Environmental zone	Remarks
India (Karnataka) (Orissa)	2	1	Very hot, humid
Indonesia (all areas)	2	1	Very hot, humid
Philippines (all areas)	3	1	Very hot, humid
Zambia (Mt. Makulu)	1	1	Very hot, humid transition from zone 1 to 2, summer planting
Bangladesh (all areas)	3	2	Hot, dry winter, dews common in winter
Myanmar	1	2	Hot, humid
India (M.P.)	2	2	Hot dry, frost can occur
Madagascar	1	2	Hot, humid
Somalia	1	2	Hot to very hot, humid
Thailand (all areas)	3	2	Generally dry winters; dews common
Vietnam	2	2	Early part of season dry; latter part moist
Zambia (Mt. Makulu)	1	2	Winter planting, dry season
Brazil (Paraná, R.G.)	2	3	Warm, humid
Burundi	1	3	Warm, humid
China (South)	1	3	Warm, humid
India (U.P.)	2	3	Warm, dry winters; dews common
Nepal (Terai)	2	3	Lowland warm, dry winters; dews common
Paraguay (Itapua)	2	3	Warm, humid
Tanzania	1	3	Midland areas
Zimbabwe	2	3	Warm, humid

[a] Zones: 1) Very hot—coolest month mean temperature > 22.5°C, 2), Hot—coolest month mean temperature >17.5°C, 3) Warm, temperate—coolest month mean temperature > 12.5°C.

Table 2. Scientific names of pathogens noted in tables and text.[a]

Pathogen	Disease
Alternaria triticina Prasada & Prabhu	Alternaria leaf blight
Barley Yellow Dwarf Virus (BYDV)	Barley yellow dwarf (BYD)
Bipolaris sorokiniana (Sacc. in Sorok.) Shoem. (syn. *Helminthosporium sativum* Pamm. King and Bakke)	Spot blotch, common root rot
Drechslera hawaiiensis (Bugnicourt) Subram. & Jain ex M.B. Ellis	Leaf blotch
D. tritici-repentis (Died.) Drechs. (*syn. H. tritici-repentis* Died).	Tan spot
Erysiphe graminis DC f.sp. tritici E. Marchal	Powdery mildew
Fusarium graminearum Schwabe	Scab
Gaeumannomyces graminis var. *tritici* Walker	Take-all
Puccinia recondita Rob. ex Desm. f.sp. *tritici*	Leaf rust
P. graminis f.sp. tritici Eriks. & Henn.	Stem rust
Septoria tritici Rob. in Desm.	Septoria tritici blotch
S. nodorum (Berk.) Berk.	Septoria nodorum blotch
Sclerotium rolfsii Sacc.	Sclerotium foot rot
Tilletia indica (syn. *Neovossia indica*)	Kamal bunt
Ustilogo tritici	Loose smut
Xanthomonas campestris pv. translucens (J.J. & R) Dye (*syn. X. translucens* (J.J. & R) Dows. var. *undulosa*)	Black chaff and Bacterial leaf streak

[a] Names taken mostly from Weise (1987).

Table 3. Research specialties of questionnaire respondents.[a]

Specialty	Percentage of scientists working in these specialties[b]
Foliar diseases	70
Breeding/genetics	40
Rusts	37
Soilborne diseases	33
Chemical control	33
Mycology	27
Epidemiology	27
Resistance	27
Others (seedborne, smuts)	13
Etiology	3
Bacteriology	3
Virology	3
Biological control	3
Nematology	0

[a] Questionnaires from 30 respondents used. CIMMYT scientists omitted.
[b] Most respondents work in multiple specialities thus percentages do not add up to 100%.

Scientists' perceptions of the economic importance of specific wheat pathogens

In environmental zone 1, the coolest month of the year has an average temperature equal to or greater than 22.5°C. Countries placed in this zone are Indonesia and the Philippines. Summer plantings in Zambia, and the southern, nontraditional wheat areas in India, like Karnataka and Orissa, fall into these truly nontraditional, very hot and humid areas. Relatively speaking zone 1 has little wheat area (Table 4).

Information in Table 5 is based on eight questionnaires received from zone 1. The ratings were obtained by taking a simple average of responses in each category over the total number of responses. "No rating" indicates that the respondent didn't think the pathogen important enough to give a

Table 4. Crop management practices, rotation crops planned or presently rotated with wheat, and area in tropical or semitropical regions.[a]

Country	Crop management practices	Principal crops planned to be or presently rotated with wheat	Subtropical & tropical wheat area (ha)
Bangladesh	animal, tractor power, broadcast, hand weed, fertilizer, irrigated	rice, jute	600,000
Brazil	tractor, direct drill or conventional, pesticides ,burn debris or leave, rainfed	soybeans, pulses, rape	1.4 million
Burundi	manual power, broadcast, hand weed	maize, beans	9,000
China (South)	tractor, & animal power, seed in rows, hand weed, irrigated	rice, maize	500,000
India, Orissa Karnatkata M.P., U.P.	tractor & animal power, hand weed, pesticides, burn debris, irrigated & rainfed	Orissa: rice, peanut, vegetable; Karnatkata: rice-peanut, pulses; M.P.: soybean, rice, potato, peanut, fallow; U.P.: rice, cane, pulses, maize, potato, toria	56,000 (Orissa) 3.4 million (M.P.) 16.6 million (U.P.)
Indonesia	land prep by tractor, hand plant in rows, hand weeding, insecticide, burn debris	rice, maize	-

Table 4. Continued.

Country	Crop management practices	Principal crops planned to be or presently rotated with wheat	Subtropical & tropical wheat area (ha)
Madagascar	animal power or manual power, hand seed in row, hand weed, incorporate debris, rainfed	rice, potato, vegetable, forages	3,000
Myanmar	animal power, broadcast or in rows, hand weed, burn debris, rainfed	fallow, maize	120,000
Nepal	mostly animal power, broadcast, hand weed, partial irrigation	rice	315,000
Paraguay	tractor power, drill seed, pesticides, chemical, weed control, debris plowed or burned, rainfed	soybeans	230,000
Philippines	animal power, insecticides, burn debris, pesticides	rice	50
Somalia	tractor power, drill by hand, herbicides & hand weed, pesticides incorporate debris, irrigated	rice, maize	4,000
Tanzania	manual & tractor power, broadcast or drill seed, some herbicide, burn debris, plow or graze	fallow, maize, bean	60,000
Thailand	animal & tractor power, broadcast & rows, hand weed, burn debris, irrigated, rainfed	rice, maize, soya	800
Vietnam	tractor power, plant in hills or broadcast, hand weeding, fungicides	rice, soybeans, beans	60,000
Zambia	tractor power, some direct drill, pesticides, some hand weeding, burn debris or leave, rainfed (summer/1,000 ha) & irrigated (winter/10,000 ha)	soybeans, maize	11,000
Zimbabwe	tractor power, conventional or zero till, drill seed, herbicides, irrigated	maize, soybeans, cotton	45,000

[a] Based on responses from 31 questionnaires. See Table 1 for the zone designations of each country.

rating within categories 1 to 5 (1 = most important, 5 = least important). This analysis is the same used for Tables 6 and 7.

It is clear that the surveyed scientists feel that, of the foliar diseases, *B. sorokiniana* is the major economic pathogen in this region. It is rated by 63% of the respondents in category 1. Another measure of its importance is that all respondents gave it a rating between 1 and 3.

It appears that fusarium scab and leaf rust are the second and third most important diseases occurring in most of these areas. Others are of sporadic or isolated occurrences. Interestingly, the areas where *A. triticina*, *D. hawaiiensis*, and BYDV occur are all in southern India. *S. rolfsii* was noted as the most important overall of soilborne diseases with some presence of *Fusarium* spp. and *Rhizoctonia* spp.

Table 6 shows the results for environmental zone 2 (mean temperature in coolest month between 17.5-22.5°C). This zone is considered generally hot and humid and, if not very humid, dews still are common. Zone 2 contains large areas of commercial wheat, principally in India, Bangladesh, and Myanmar (Table 4).

Again *B. sorokiniana* is clearly felt to be the most economically important foliar pathogen. It appears in most of the areas surveyed. *P. recondita* appears second in importance with fusarium scab third. We feel that the rating of *P. graminis* noted from Madagascar, Vietnam, and Zambia may be spurious, but more information is needed to determine this. *S. nodorum* may need confirmation in Somalia and Vietnam. As known, the pathogen flora may change with the environmental zone, thus several new pathogens adapted to hot, humid climates are noted, but are only of importance in certain areas. Soilborne diseases are led by *S. rolfsii*, followed by *Fusarium* spp., *Rhizoctonia* spp., and *B. sorokiniana*.

B. sorokiniana continues to appear as the economically most important foliar disease, even in the relatively cooler areas

Table 5. Scientists' perceptions of the economic importance of specific wheat pathogens: Environmental Zone 1, very hot.

Pathogen	Percentage of scientists' ratings in each category[a]				No rating
	1	2	3	4	
Foliar or head					
B. sorokiniana	63	25	12	0	0
Fusarium sp. (head)	12	38	0	12	38
P. recondita	12	0	12	12	63
A. triticina	12	12	0	0	75
D. hawaiiensis	12	0	0	0	88
BYDV	0	12	0	0	88
P. graminis	0	12	0	0	88
X. campestris	12	0	0	0	88
Soilborne					
S. rolfsii	25	50	0	0	25
Fusarium spp.	0	12	12	0	75
Rhizoctonia spp.	0	0	12	0	88

[a] Rating of importance: 1 = most important: 5 = least important. Rating of 5 was not given in this zone.
See Table 1 for countries in Zone 1.

Table 6. Scientists' perceptions of the economic importance of specific wheat pathogens: Environmental Zone 2, hot.

Pathogen	Percentage of scientists' ratings in each category[a]					No rating
	1	2	3	4	5	
Foliar or head						
B. sorokiniana	43	36	7	0	0	14
P. recondita	36	14	29	0	0	21
Fusarium spp. (head)	14	0	7	7	0	72
P. graminis	14	7	0	0	0	79
D. tritici-repentis	7	7	0	0	7	79
S. tritici	0	7	7	0	7	79
Alternaria spp.	0	14	0	0	7	79
E. graminis	0	14	0	7	0	79
S. nodorum	0	0	0	7	7	86
Soilborne						
S. rolfsii	36	7	29	7	0	21
Fusarium spp.	0	21	0	0	14	65
Rhizoctonia spp.	0	7	14	0	0	79
B. sorokiniana	0	0	0	17	0	93

[a] Rating of importance: 1 = most important: 5 = least important.
See Table 1 for countries in Zone 2.

Table 7. Scientists' perceptions of the economic importance of specific wheat pathogens: Environmental Zone 3, warm.

Pathogen	Percentage of scientists' ratings in each category[a]					No rating
	1	2	3	4	5	
Foliar or head						
B. sorokiniana	31	23	8	15	15	8
P. recondita	39	23	15	0	8	15
P. graminis	8	15	15	15	15	32
D. tritici-repentis	23	8	8	15	8	38
Fusarium spp. (head)	8	15	8	8	23	38
E. graminis	0	8	23	8	8	53
S. nodorum	8	0	15	8	15	54
X. campestris	0	8	23	0	8	61
S. tritici	8	8	8	8	0	68
T. indica	0	0	8	0	8	84
U. tritici	0	0	8	8	0	84
Soilborne						
Fusarium spp.	0	8	0	8	15	69
G. graminis	8	0	0	8	8	76
B. sorokiniana	0	0	0	8	0	92

[a] Rating of importance: 1 = most important: 5 = least important.
See Table 1 for countries in Zone 3.

of zone 3, where the temperature in the coolest month is between 12.5-17.5°C (Table 7). This climatic zone represents millions of hectares (Table 4) and is the largest and coolest in what we are considering the warmer wheat environments. Thirteen questionnaires were used in this analysis. *P. recondita* is a priority disease in this area as is *P. graminis*. *B. sorokiniana* also maintains importance. *D. tritici-repentis* and fusarium scab appear important in many countries and *E. graminis* somewhat less so. *S. nodorum* and *S. tritici* are noticed in some areas. *X. campestris* pv. *translucens* is in several places. *T. indica* and *U. tritici* are noted in India. *Fusarium* spp. appear to be the most important soilborne pathogens in the cooler areas followed by *G. graminis* and *B. sorokiniana*.

An attempt was made to ascertain yield losses and the frequency of disease occurrence in the three environmental zones. Respondents were asked to estimate losses on a scale of 1 to 5, equivalent to a range of percentage losses (Table 8). The table presents the average score and the range of scores as a measure of range of losses. Frequency of occurrence by years is also presented in the same manner. It is apparent that scientists' estimates in Tables 5, 6, and 7 correlate highly with their perception of yield losses in Table 8. *B. sorokiniana*, as a foliar pathogen, is considered, on

Table 8. Scientists' estimates of yield losses due to wheat diseases and frequency of disease occurrence by environmental zones.[a]

Pathogen	Yield loss by zone			Frequency of occurrence in years by zone		
	1	2	3	1	2	3
Foliar or head						
B. sorokiniana	3.1(1-5)[b]	3.1(1-4)	4 (3-5)	1.1(1-2)	1.6(1-3)	1.2(1-3)
P. recondita	2.3(1-5)	3 (1-4)	3.8(3-5)	1.3(1-2)	1.2(1-2)	1.6(1-4)
Fusarium spp. (head)	3.3(2-5)	2.5(1-4)	3.3(1-5)	1.3(1-2)	1	1.8(1-3)
P. graminis	4	2 (0-3)	3.7(2-5)	1	1	1.4(1-3)
D. tritici-repentis	0	2	3.6(1-5)	0	1	1.3(1-2)
E. graminis	0	1.5(1-2)	2.5(2-3)	0	1	1.8(1-3)
S. tritici	0	2	2.3(2-3)	0	1	1.8(1-4)
BYDV	1	0	2	1	0	2
A. triticina	3	2	0	1	1	0
D. hawaiiensis	4	0	0	1	0	0
S. nodorum	0	0	2	0	0	1.6(1-3)
X. campestris	0	0	3 (2.5)	0	0	1.8(1-3)
T. indica	0	0	2	0	0	3
Soilborne						
S. rolfsii	3 (1-4)	2.9(1-5)	2	1	1.1(1-2)	1
Fusarium spp.	3 (2-4)	3.5(3-4)	1	1	1	1
Rhizoctonia	4	2	0	1	1	0
B. sorokiniana	0	3	2	0	1	1
G. graminis	4	0	1.7(2-4)	1	0	1

[a] Not all respondents answered these questions. Averages are based on number of questionnaires answered. See Table 1 for definitions of environmental zones.

[b] Scale: 0 = No loss; 1 = 0-0.2%; 2 = 0.3-1%, 3 = 1.1-5.0%; 4 = 5.1-20%; 5 = 21-100%. Scale modified from Murray and Brown (1987). Average loss + range in parentheses where there is more than one observation.

average, to be causing losses between 1 and 20% depending on the area. This occurs essentially on a yearly basis. *P. recondita* is considered almost as damaging, especially in the cooler zones. Fusarium head scab and *P. graminis* are damaging in specific areas. Thus the above pathogens appear to be the most important in causing yield losses in all three zones. *D. tritici-repentis* appears to be important in zones 2 and 3 and this is consistent with the other observations (Tables 5-7). *S. rolfsii* and *Fusarium* spp. are considered most damaging as soilborne pathogens in the hotter environments.

An anomaly occurs with respect to *P. graminis* in that no respondent rated it as economically important in zone 1 (Table 5), but one did note it as causing significant losses. Similarly, *S. rolfsii* was not rated in zone 3 (Table 7), but was noted in yield losses in that zone.

Little quantitative data are available on yield losses due to diseases noted in this paper. We, therefore, tried to consolidate available data sent by respondents, some published recently, as well as some unpublished information (Table 9).

Most information is derived from chemical control trials on experiment stations. Thus, we see potential yield losses due to these diseases, not actual. Nonetheless, potential losses appear to be great. Very few surveys have been done in these areas, but two—fusarium head scab in China and *B. sorokiniana* root rot in Brazil—show that significant losses can occur. The seed treatment data from Bangladesh were the results of 87 farmer demonstrations country-wide and, thus, the 10% loss estimate would appear to be reasonable for much of the country that year.

Crop management practices, rotations, and hectarage will have a significant influence on disease occurrence and development. Thus, it was felt worthwhile to bring the available information together from the questionnaire in tabular form (Table 4). In 9 of the 17 countries, rice is the major rotation crop as well as by hectarage. Soybeans and maize appear important too. It can be seen that many combinations of management practices are used in the wheat grown in the warmer areas. By far, the largest area of wheat in the warmer climates exists in South Asia, i.e., Bangladesh, India, and Nepal (Table 4).

Respondents were asked whether there were interactions between diseases noted in the questionnaire. Fifty-five percent said yes, 39% no, and 6% had no answer. One salient comment was that, as *B. sorokiniana* resistance increased, leaf rust increased, apparently due to more available healthy tissue. It was felt that foot rots interacted among themselves and with foliar blights.

As it is thought that crop management can greatly affect diseases, respondents were asked if they felt there were interactions between the major diseases and management practices and, if so, what they felt they might be. Ninety percent agreed that there were interactions, 7% said no, and 3% had no answer. Based on field observations, it was felt that rust and powdery mildews increased with excess nitrogen. Maize debris contributed to scab incidence and conservation tillage practices increased stubble-borne diseases. In some cases, poor weed control and high plant density increased disease, e.g., *B. sorokiniana*, the cause of spot blotch on leaves.

Soil fertility status apparently can affect diseases and the respondents were asked if they agreed. Seventy percent said yes, 15% no, and 15% had no answer. Interestingly, most of the answers dealt with observations on interactions with spot blotch. Low fertility and unbalanced

nitrogen appeared to increase spot blotch. Some felt that potassium application seemed to aggravate spot blotch and liming increased take-all.

We asked if diseases from rotation crops appeared to affect wheat; 41% said yes, 41% said no, and 18% did not know. Fusarium cob rot of maize was considered to increase wheat scab. Sclerotium foot rot appeared to increase in wheat after peanut or rice. *Meloidogyne naasi* was associated with wheat after rice. Rhizoctonia sheath blight also increased in wheat in a rice-wheat rotation.

In response to a question regarding the suspected importance of cryptic (unidentified) soilborne diseases or viruses, 40% felt they could be and 40% felt they were not significant. The most consistent answer was that stand establishment was low in many areas for unknown reasons.

Table 9. Yield losses caused by wheat pathogens in controlled trials or limited surveys in the warmer areas.[a]

Pathogen	Country	Percent loss estimate[b]	Remarks	Reference
B. sorokiniana (foliar)	Bangladesh	24	Chemical control trials	D. Saunders (pers. comm.)
	Brazil	30-80		Mehta (1985)
	Philippines	40	Chemical control trials	Lapis (1985)
	Zambia	45	Chemical control trials	Raemaekers (1985)
P. recondita	Brazil	4-70	Chemical control trials	Mehta & Igarashi (1985)
	India	40	Chemical control trials	Singh & Singh (1975)
	Vietnam	12-22	Fertilizer trials with rust control	H.M. Trung (pers. comm.)
Fusarium spp. (head)	China	5-40	Surveys—Yangtze River area	Liu (1985),
	China	10-40		Wang (1988)
	Paraguay	4	Natural field infection	de Viedma (1987)
D. tritici-repentis	Nepal	20-30	Mostly *D. tritici-repentis* with some *B. sorokiniana*. Chemical control trials	H.J. Dubin & H.P. Bimb (unpubl.)
BYDV	Worldwide	1-93	Artificial inoculation & natural infection	Pike (1990)
E. graminis	India	23	Chemical control trials	Singh & Saxena (1973)
Soilborne complex	Bangladesh	10	Seed treatments—farmer demonstrations	Razzaque (1989)
	Nepal	5-9	Chemical control & soil solarization trials	H.J. Dubin & H.P. Bimb (unpubl.)
S. rolfsii	India	20-30	Survey—Madhya Pradesh	Pathak (1989)
	India	5-8	Karnataka	Hedge et al. (1980)
B. sorokiniana (soil)	Brazil	9-23	Survey	Diehl et al. (1982)

[a] Mostly from CIMMYT (1985), Klatt (1988), and information sent with questionnaires, published and unpublished.
[b] In most cases, represents potential losses based on fungicide control trials of various types.

The last question asked the respondents whether government interest in wheat pathology was significant. Sixty-five percent answered yes, 29% no, and 6% did not answer. The two main reasons for problems were lack of cooperation between institutions and insufficient funds.

Discussion of Questionnaire Results

In relation to the research interests of the respondents, some might feel that bias was introduced since the questionnaires were only sent to general pathologists and pathologist/breeders rather than virologists, bacteriologists, or nematologists. However, there are few to no researchers working full time in these fields on wheat in the warmer climates. Thus, the results appear realistic. Brazil is an exception to this because virologists (working on BYDV and SBWMV) and bacteriologists (working on *X. campestris* pv. *translucens*) are there. However, we are not aware of similar situations in other countries.

The small effort in biological control in these areas is not surprising, but lack of mention of crop management measures or integrated pest management (IPM) would indicate that there continues to be little real integration of efforts, especially between pathology and agronomy. Increased cooperation between these disciplines in the previous symposium in Thailand was considered an important need (Mehta and Raemaekers 1988) and we believe it more so than ever.

B. sorokiniana, overall, is considered to be the most important pathogen to overcome in all environmental zones. It is not realistic to put too much credence in the precise rankings in Tables 5, 6, and 7. Suffice it to say that the respondents feel that fusarium scab and *P. recondita* are deleterious to production in all the zones. *P. graminis* is noted in zones 2 and 3 and *D. tritici-repentis* shows up particularly in the cooler zones. It would seem that research priorities relating to foliar pathogens have been appropriate, based on the published literature (CIMMYT 1985, Klatt 1988). However, we think it worthwhile to mention that perceived damage caused by *P. graminis* may be more potential than actual, based on personal observations.

Most of the other pathogens are restricted to small areas, but it would be a mistake to ignore any of these. Too often, minor diseases become major ones because they were overlooked. *X. campestris* pv. *translucens* and *E. graminis* have recently been observed more often on the Indian Subcontinent as has BYDV (H.J. Dubin, unpublished). As cultural practices and climate change, we can expect disease patterns to change. In 1990, in lowland Nepal we saw a rapid increase in *B. sorokiniana* as a foliar blight where we normally see *D. tritici-repentis*. We attribute this change to abnormal weather patterns—especially due to warm night temperatures in January 1990.

In the hottest zones, *S. rolfsii* is considered the most severe soilborne problem and *Fusarium* spp. appear second. *Rhizoctonia* sp. is also noted in these areas although no mention is made of the species.

B. sorokiniana foot rot is present in the cooler zones, but it is very probable that it is important in zone 1 but overlooked. *S. rolfsii* is not listed in zone 3 while *G. graminis* does appear.

It is our contention that soilborne maladies are too easily overlooked and, in many cases, these are causing significant losses, especially in suboptimal years. We think the foliar or head pathogen estimates in Table 8 may be reasonable, but the soilborne ones are less so. Again, it is probable that *B. sorokiniana* is more important than noted.

Occurrences of the noted diseases seem to be frequent, occurring on average, between 1 and 2 years (Table 8). Thus, it seems that diseases in these areas appear commonly rather than sporadically. Frequent occurrences would generally, but not always, indicate yield loss problems.

Yield loss assessments due to diseases are a prerequisite to the setting of appropriate research priorities. However, a limiting factor in doing the necessary research is the lack of appropriate methodologies (Chiarappa 1981). Where methods are available, they require a good deal of work in farmers' fields, which is difficult, although necessary, in most Third World countries. Little objective yield loss estimates are available for wheat in the warmer areas to help determine if informed opinions are correct. Table 9 is an attempt to present literature dealing mostly with potential losses and, in a few cases, actual losses surveyed.

Worthy of special mention is the seed treatment in Bangladesh where 10% yield loss countrywide was determined (Razzaque 1989). Chemical control trials of foliar blights in 1990, especially of *B. sorokiniana*, in Bangladesh indicate significant losses as well. Trials at four sites indicated a 24% yield loss with cv Kanchan (D. Saunders, pers. comm.). No appropriate loss estimates are yet known in farmers' fields, however. Nevertheless, we can theorize that there are very significant losses due to foot rots and foliar blights that are priority research issues. Similar situations probably exist in other warmer countries.

The last group of questionnaire responses was utilized to obtain information on interactions among diseases, as well as diseases, hosts, and cultural practices. We also wanted to see if the importance of interactions was clearly perceived by the respondents. The traditional rust diseases are generally looked at singly, too often, without determining whether there are interactions with other diseases or management practices. Predisposition to diseases caused by interactions with other pathogens and management practices is now beginning to attract attention. This phenomenon is bound to be even more important in nontraditional areas where environment is suboptimal and host and pathogen have not co-evolved (Dubin 1985).

The answers to the questions presented, in general, show that the respondents are aware and concerned about interactions. Nonetheless, based on literature reviews, reports, and information sent to us, almost no experimental work is being reported in relation to these types of studies in the warmer wheat areas. This is especially problematic since disease control in these areas will, almost certainly, depend upon integrated control strategies (Dubin 1985).

Two areas where less than half the respondents gave positive replies were whether the rotation crop interacted with diseases and the existence of cryptic diseases. The fact that 18-20% said they didn't know is more significant than the "no" answer. These would appear to be research issues.

Overview of New Results on Key Diseases in Warmer Areas

This section of the paper provides an update on key diseases since the last symposium in Thailand in 1987 (Klatt 1988).

Spot blotch and common root rot (*B. sorokiniana*)

In relation to spot blotch, almost all literature for the warmer areas is related to international efforts in networking among Brazil, Germany, Israel, and CIMMYT. Other countries are also contributing information to this network.

Most information on *B. sorokiniana* as a root rot organism comes from the more temperate climates where it is a confirmed pathogen in certain areas. Why the difference in emphasis? It is generally felt that spot blotch is not very important in the temperate regions but, as noted before, we feel that soilborne diseases in the warmer areas except the most obvious are underrated.

Recent information presented by Mehta and Riede (1989) on resistance to spot blotch shows cvs. LD 7831, CNT 1, BON/YR/3/F35.70//KAL/BB, CEP76146, PAT7219, Trigo BR 8, Anahuac, KVZ/HD2009, BH 1146, and PF7339 as being "relatively more resistant" than other germplasm tested. Importantly, they are now using a recurrent selection program to build up higher levels of spot blotch resistance. Studies on the genetics of resistance in key lines have been initiated.

The recently formed Indian national project on foliar diseases presented a report in 1989 indicating that *B. sorokiniana* appeared to be the major pathogen surveyed with several *Alternaria* spp. and *H. tetramera* McKinney also fairly common. (Singh et al. 1989).

The networking project noted previously presented a progress report (Fehrmann et al. 1989): Incorporation of Resistance to *Helminthosporium sativum* in Wheat. The research deals with screening for resistance and tolerance, use of toxins for selection of resistance, and incorporation of resistance into well adapted germplasm. Studies are also being done on inoculation techniques and determination of differential varieties for race identification (Hetzler et al. 1991). Our own screening work for resistance in Nepal over the last 2 years indicates that progress is being made in resistance to spot blotch since improved levels of resistance are observed in lines coming from spot blotch areas like Zambia and Brazil. Thus, disease pressure is allowing selection of better materials. For some unexplained reason, several Chinese lines as well as Chinese/CIMMYT crosses are showing good resistance.

Further, field testing of alien gene lines from CIMMYT, first with *D. tritici-repentis* and then with *B. sorokiniana* showed good resistance. Reaction phenotypes and rate of increase differed from the pure wheats in many cases. Crosses especially with *Agropyron curvifolium* showed good resistance to both diseases. It appears that different sources of resistance are available for combining (H.P. Bimb and H.J. Dubin, unpubl.). It should be noted that not all lines with *B. sorokiniana* resistance served for *D. tritici-repentis* nor was the resistance as good. Fehrmann et al. (1989) noted some lines that had moderate levels of resistance to both foliar blights.

It is felt that the more "cryptic" foot rots caused by such pathogens as *B. sorokiniana*, *Fusarium* spp., *Pythium* spp., and others will be determined as more important when well executed surveys are done such as published by Specht and Rush (1988) in Texas. They showed that *B. sorokiniana* was the major foot rot pathogen in the Texas Panhandle.

Bailey et al. (1988) confirmed that reasonable resistance to *B. sorokinana* foot rot phase is obtainable. Heritability estimates were high and indicated that selection could be started in early generations in some cases. However, advanced generations gave higher heritabilities overall. Resistance appeared to be controlled by three genes in the crosses tested.

Leaf rust (*P. recondita*)

Recent efforts at CIMMYT and the University of Sydney, in conjunction with Indian and Pakistani research

institutions, are shedding new light on the diversity and genetic basis of resistance in the semidwarf wheats.

Preliminary studies at CIMMYT indicate a broad level of combinations of major genes in 50 different semidwarf wheats. As well, experiments on adult partial (rate limiting) resistance indicate the CIMMYT germplasm contains significant amounts. In past years, it had been felt that the *Lr13* "complex", derived from Frontana, had been giving good levels of durable resistance. Recent evidence, however, indicates that *Lr34* together with three or four other genes, interacting additively, may be even more important (R. Singh, unpubl.).

The University of Sydney collaborative rust project with India and Pakistan aims to determine the genetic basis of rust resistance in wheats grown in India and Pakistan. Shuttle breeding, single seed descent methodology, and gene matching techniques are being used to determine the presence of resistance genes. As in the CIMMYT work, significant amounts of adult plant leaf rust resistance are observed (R.A. McIntosh, pers. comm.).

Similarly, work in India by Gupta and Saini (1987) indicates that, besides *Lr13*, there appears to be other adult plant leaf rust resistance conferring good resistance in a wide range of Indian wheats.

In recent years, there has been concern in South Asia that *Lr26*-bearing wheats, such as the Veerys and Bobwhites, may have a narrow spectrum of leaf rust resistance. Field observations in India where *pLr26* races exist show that many of these 1B/1R lines clearly have additional functional resistance genes (H.J. Dubin, unpublished).

Tan spot (*D. tritici-repentis*)

D. tritici-repentis has become a very important disease in the last 2 decades or so. Its increase has been generally associated with modified practices such as conservation tillage (Rees and Platz 1990). It is probable that modern, semidwarf plant architecture has contributed as well, especially in the warmer areas.

In many parts of the warmer areas, especially Brazil and Nepal, *D. tritici-repentis* and *B. sorokiniana* are commonly found together on the same leaves causing foliar blights. Da Luz and Bergstrom (1987) recently showed that *B. sorokiniana* is antagonistic to *D. tritici-repentis*. In mixed infections, overall symptom production is reduced, and *D. tritici-repentis* conidial germination is lowered, among other factors.

It would be useful to see if this phenomenon exists under natural conditions. Field observations in Nepal indicate that when one disease prevails the other is down, but this may simply be due to environment rather than antagonism. The questionnaire data would indicate that *D. tritici-repentis* is adapted to slightly cooler conditions than the foliar phase of *B. sorokiniana* (Tables 5, 6, and 7).

Chemicals may be an integral part of conservation tillage practices, especially herbicides. Sharma et al. (1989) show that glyphosate was effective in reducing pseudothecia production on straw. It was not determined if the fungicidal activity was due to the herbicide proper or nonherbicidal components. These types of studies are very important when new management practices are initiated.

Pathotype variation in *D. tritici-repentis* has been reported over the years. Often discrepancies as to resistance or susceptibility of lines was reported. This could have been due, at least in part, to methodologies as well as virulence differences of the isolates (Lamari and Bernier 1989a). Lamari and Bernier (1989a) reported pathotype designations

based on the ability to produce both tan necrosis and obvious chlorosis (nec+chl+), chlorosis only (nec-chl+), and tan necrosis alone (nec+chl-). The basis of these designations appears to be, in part, due to the reaction of a heat labile toxin. Toxin production of the pathogen was associated with the ability of individual isolates to induce tan necrosis (nec+) in necrosis expressing cultivars. Isolates that induced extensive chlorosis, but not necrosis (nec-chl+), did not produce this *in vitro* toxin and virulence should be due to another toxin and/or mechanism than that functioning in the necrotic reaction (Lamari and Bernier 1989b). These results may partially help explain why a known resistant line, BH1146, sometimes shows up susceptible. It appears only resistant to pathotype nec-Chl+ according to Lamari and Bernier (1989b), thus it is susceptible to the noted toxin. The above data give the basis for a re-evaluation of pathotype specificity in *D. tritici-repentis*.

Recent papers have shown good resistance available to *D. tritici-repentis* in complete bread wheats (Rees and Platz 1990). Others have shown high levels of resistance to be present in "wild" wheats or progenitors (Alam and Gustafson 1988, Lamari and Bernier 1989c).

Soilborne disease complex

The area of soilborne diseases is one of the most difficult to research and thus new literature is less than in other areas, especially in the Third World. Some interesting information recently published is given to emphasize and focus on what we feel are important needs.

Nematodes as pathogens and their interactions with fungi have not been given sufficient attention in wheat. Recent evidence at CIMMYT confirms earlier reports of *Pratylenchus thornei* Sher and Allen on wheat in Yaqui Valley and the high plateau of Mexico (D. Lawn, pers. comm.). Some CIMMYT germplasm displays good resistance to this nematode in Australia where yield losses can be significant. The wheat program in Queensland has an active breeding program for resistance and tolerance to *P. thornei* (D. Saunders, pers. comm.). Kimpinski et al. (1989) showed that root lesion nematodes, primarily *P. penetrans*, significantly lowered wheat yields on Prince Edward Island, Canada. However, they did not find an interaction between fungal foot rot or foliar blight pathogens and nematodes. Effects were additive. More of this type of research is warranted.

Results in India show that cereal cyst nematode, ear cockle, and more recently stunt nematode (*Tylenchorenchus vulgaris*) are problems in certain areas (Sethi 1988).

In Nepal, 10 years of yield data indicate stagnating or declining yields at the National Wheat Development Program and preliminary evidence indicates that soil pathogens are a factor (H.P. Bimb and H.J Dubin, unpubl.).

Neypes et al. (1988) highlights the effort on biological control of soilborne diseases. Their results show significant control of *S. rolfsii* on wheat with *Trichoderma glaucum* Abbot applied as a seed dressing or incorporated in the soil. Biological control should be emphasized as one part of an integrated, sustainable control program.

Outlook for disease control in warmer areas

The key word in relation to disease control in the warmer areas should be "integrated". At the previous workshop in Thailand, we stressed the need for integrated efforts as well (Mehta and Raemaekers 1988). We will differentiate integrated control (IC) from integrated pest management (IPM). IC as we see it deals with emphasis on one pest. It is multicomponent, stressing integration of strategies, action thresholds, and

environmental assessments. IPM stresses pest complexes of all sorts and may include IC (Andrews 1983).

Within the concept of IC, we can include genetics, crop management, biological, and chemical controls. Thus, we think the outlook for wheat disease control in the warmer areas will be brightest if an integration of methods is utilized. As noted previously, we are growing wheat under suboptimal conditions in contact, often, with nontraditional micro-organisms. No single control method may be adequate.

Genetic approaches should emphasize the incorporation of durable types of resistance. The ecosystem where the crop will be grown determines the amount of resistance needed and it will also determine where it is most useful to breed and select for the most long lasting resistance (Buddenhagen 1983). In most cases, we are working in the proper areas and must continue to do so. In the specific cases of spot blotch and tan spot, recurrent selection systems seem to hold good promise for obtaining useful levels of resistance especially when testing in places like Brazil, Nepal, and Zambia.

For many years, we have strongly advocated linkages among pathologists, agronomists, and breeders. We must work more than ever as a team. The issues of sustainability, yield stagnation, and/or decline requires an interdisciplinary research approach. It is now well known that management practices have affected wheat diseases and the remedies require the efforts of agronomists, pathologists, soil scientists, and others. Engelhard (1989) has published an excellent new publication on management of diseases with macro- and microelements. It should be very useful in research efforts on soilborne diseases. One special point worth mentioning is, in researching new controls in management we should not forget to look at the past. Thurston (1990) points out some traditional methods, like raised beds, to control diseases. We who work in these areas should be cognizant of traditional methods and their utility.

Biological control is becoming more possible in wheat diseases than ever before. Bacterization, use of suppressive soils, antagonists, and predators are all becoming feasible. Thompson and Wildermuth (1989) have just shown that vesicular-arbuscular mycorrhizae (VAM) can reduce root infections by *B. sorokiniana*. Recombinant DNA methods will provide more tools to manage diseases in the future.

Chemicals will continue to provide important control measures for wheat diseases. However, keeping in mind environmental and product costs it is obvious that strategies to increase efficiency are necessary. More selective types of chemicals will be produced and better methods of application developed.

Several final points are worthy of mention. Functional diversity will be important in minimizing risks to subsistence farmers and this may come in the form of cultivar mixtures, multilines, or varietal deployment.

An integration of the above strategies will provide the best overall disease control. Remember, however, that there will not be a best disease control strategy for everyone and that the strategy must be consistent with farmers' goals.

Recommendations for Future Research

Research priorities were enumerated in the Thailand conference and only little progress has been made in relation to these (Mehta and Raemaekers 1988). We would like to add on to, or emphasize some of those made in 1988. The following

then, are some ideas, not to be considered a complete list nor are they necessarily in order of priority:

- Increased survey efforts and loss quantification.
- Improved diagnostics.
- Improved methodologies for disease scoring.
- Etiology and epidemiology of important diseases.
- Development of disease management strategies based on understanding of the interactions of abiotic and biotic plant stresses.
- Increased effort on foliar blights and soilborne diseases, their interactions, and control.
- Research on durable resistance.
- Research to minimize postharvest losses.
- Study of useful traditional control methods.
- Research on use of computers to help us increase our ability for data collection and analysis, networking, and communications.

Concluding Remarks

We have attempted to give a status report of the wheat disease situation in the warmer areas. As well, an update on new research information since the last workshop is given for some key diseases. Finally, some ideas for future disease control efforts and recommendations for future research are presented. Based on the questionnaires, it seems that empirical methods of determining disease importance were basically correct. However, scientific surveys and loss quantification would help us prioritize and conserve much needed resources.

The fact that little literature, even in national publications, was found indicates that insufficient research is being done on pathology of wheats in the warmer areas. To a great extent what is done is screening for disease resistance in a routine manner. Although this is very important, we need in depth knowledge about key diseases if we are to design appropriate disease management methods for use in the warmer areas.

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Resumen

Se envió un cuestionario a los investigadores de trigo de las zonas más cálidas del mundo en desarrollo con el fin de determinar la situación en cuanto a las enfermedades del trigo y las investigaciones en esas regiones. Si bien este método carece de la precisión deseada, permite llegar a una estimación mundial de las percepciones que tienen los investigadores de trigo de los efectos de las enfermedades y la información correspondiente.

Los datos sobre la importancia de las enfermedades se presentan por zonas agrupadas según la temperatura. Se confirma que Bipolaris sorokiniana es el agente patógeno foliar económicamente más importante en todas las zonas. Puccinia recondita y la roña por Fusarium parecen importantes en todas las zonas, mientras que Drechslera tritici-repentis parece serlo principalmente en las partes más frías de las zonas cálidas. En las dos zonas más cálidas, Sclerotium rolfsii y las especies Fusarium representan las enfermedades transmitidas por el suelo más perjudiciales y, en la zona más fría, predominan las especies Fusarium y Gaeumannomyces graminis.

No se dispuso de datos cuantitativos apropiados sobre las pérdidas de rendimiento, pero los ensayos de métodos de control químico de las enfermedades revelaron considerables pérdidas reales y potenciales en esas zonas, causadas por las enfermedades antes señaladas. Se formularon preguntas acerca de las interacciones entre las principales enfermedades y las prácticas de manejo de los cultivos, la fertilidad del suelo, la rotación de cultivos y enfermedades difíciles de identificar. En la mayoría de los casos la respuesta fue afirmativa y se presentan las observaciones efectuadas.

Se considera que la escasez de información relacionada con la investigación sobre las enfermedades, aun en las publicaciones científicas nacionales, es un fiel reflejo de la situación. Se requieren encuestas objetivas y la cuantificación de las pérdidas para establecer las prioridades de las actividades de investigación. Los métodos integrados de lucha parecen ser los más lógicos para reducir las pérdidas. Sobre la base de lo expuesto anteriormente, se formulan recomendaciones para la investigación.

Interactions Between Spot Blotch (*Cochliobolus sativus*) and Wheat Cultivars

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Abstract

Spot blotch of wheat caused by Cochliobolus sativus *Ito and Kuribay triggers severe epidemics in tropical countries in Africa, Asia, and South America. Yield losses are estimated to be up to 87% in highly susceptible varieties. Control is achieved by integrated management and present research aims to incorporate host resistance. Wheat wide crosses with* Agropyron *and wild emmer accessions are being screened as resistance sources. Somaclonal variation in resistance has been found in plants regenerated from callus culture. Slow progress in breeding for resistance is a result of a combination of factors, including low resistance levels in commercial spring wheats and the wide pathogenicity spectrum of* C. sativus *isolates. Pathogenicity studies with a global collection of* C. sativus *monoconidial isolates on a differential set of wheat varieties and lines, using detached leaf tests, revealed 15 pathotypes. It was calculated for several national isolate collections that 1 to 2% of the variance is due to interaction and it is assumed that several genes for virulence are operating in the pathosystem. These results indicate a need to monitor the virulence situation in disease "hot spot" locations on a global scale which will facilitate studies on the inheritance of resistance to spot blotch.*

Economic Importance of Spot Blotch

Spot blotch (leaf blotch) of wheat incited by *Cochliobolus sativus* Ito and Kuribay (syn. *Ophiobolus sativus* Ito and Kuribay; anamorph—*Bipolaris sorokiniana* Sacc. ex Sorok.; or *Helminthosporium sativum* Pamm. King and Bakke) causes severe epidemics in tropical countries of Asia, Africa, and South America, particularly in Brazil (Mehta 1985).

The importance of spot blotch must be expressed in terms of yield losses of which there are few reports in the literature. Yield data are generated by field trials that can be difficult to undertake if either weather conditions are unfavorable for disease development or the crop is infected by several diseases. No fungicides are presently available for control of all diseases.

Estimates of yield loss widely vary. De Milliano and Zadoks (1985) found a 38% yield loss in growth chamber studies in the Netherlands using African wheat genotypes. Losses of 85% were assessed in Zambia (Raemaekers 1988) and 40% in field trials in the Philippines (Lapis 1985). In Brazil, 14 field trials undertaken between 1976 and 1983 showed losses caused by a complex of diseases (mainly leaf rust and spot blotch) to be between 22% and 59%. With field trials during 1981-1982, M.A. Oliviera (OCEPAR, Paraná, Brazil) showed losses caused by a disease complex to range between 12 and

42%, whereas losses caused by spot blotch alone were between 7 and 36% (Kohli 1985).

Estimation of yield loss by spot blotch alone has been possible in some instances. In 1982, in Palotina, Brazil, yield losses of the popular variety, Anahuac, were assessed to be between 31 and 37% (Table 1). Spot blotch was the predominant disease and butyl triazol and ethirimol were used to control other minor diseases. In 1983 in Londrina, Brazil, spot blotch was the only disease present and yield losses of the highly susceptible variety Mitacoré were between 79 and 87% (Figure 1) and grain quality was severely reduced.

Table 1. Losses in yield caused by spot blotch in wheat variety Anahuac, Palotina, Paraná, Brazil, 1982.

Fungicide (kg ai/ha)[a]	Yield (kg/ha)[b]	1000 grain weight (g)	Loss in yield (%)[c]
Ethirimol (1.0) + Propiconazol (1.0)	1.220 a	30	-
Ethirimol (1.0) + Butyl Triazol (0.6)	840 b	27	31.1
Check (without fungicide)	768 b	25	37.1

[a] A total of four fungicidal applications were made at an interval of 10 days starting from the appearance of the first symptoms of the disease.
[b] Treatments with the same letters do not differ with each other (Duncan 5%).
[c] Yield losses were calculated in relation to Treatment No. 1. Disease severities at soft dough stage in Treatments 1, 2, and 3 were 2%, 60%, and 58%, respectively.

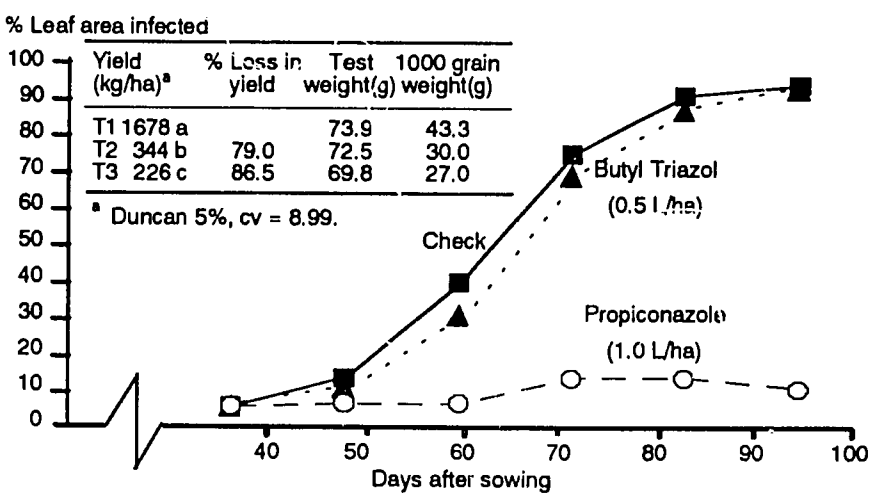

Figure 1. Effect of the fungicidal applications on progress of spot blotch on wheat variety Mitacoré, Londrina, Brazil, 1983.

Tan spot (*Helminthosporium tritici-repentis* Died.) has recently become one of the most important wheat diseases in Brazil and Paraguay and studies are underway to estimate losses caused by this disease.

Integrated Disease Management of Spot Blotch

Considering the high yield losses, emphasis is being given to an integrated pest management (IPM) approach, utilizing the following components.

Varietal resistance
Selection for spot blotch resistance in segregating populations began in the early 1980s and has recently intensified through an International Collaborative Project (Germany, Israel, Brazil, and CIMMYT) funded by the German-Israel Agricultural Research Agreement (GIARA) and the German Government. Initial progress can be seen by changes in the list of recommended varieties in Paraná where earlier highly susceptible varieties, such as Inia, Jupateco, Mitacore, P 214, and IAC 5 have been withdrawn and the new varieties, CEP 11, CEP 14, Tapejara, Igapo, Cacatu, Batuira, Pirata, and BR 8, have been included. Although accurate data on yield in the presence of spot blotch are not available, field experience indicates these new varieties to be less susceptible. Average percentage of leaf areas infected, mainly by spot blotch and tan spot in the new varieties, has been compared during the last 5 years with the susceptible varieties, Caete, Taquari, Maringa, BR 23, and BR 28 (Table 2). Eight to 82 experiments per variety per year were conducted at eight different locations incorporating five distinct wheat zones. Overall averages show some resistance in all new varieties. The large number of observations indicate even small differences in disease severity to be statistically significant. The high disease rating in Batuira in 1986 is partly due to the premature leaf senescence of this variety and, in 1987, spot blotch was favored by very warm and humid conditions.

With the exception of BR 23, most new varieties also yielded more than the susceptible varieties (Figures 2 and 3), although the yield potential of each respective variety must also have contributed to these differences.

Diversification of varieties
Severe losses caused by spot blotch can be avoided by seeding more than one variety and by seeding at different dates, but within the recommended sowing period. Farmers in Paraná are gradually adopting this practice.

Use of healthy seed
Spot blotch is transmitted by seed and efficient fungicides are available to eradicate seedborne inoculum. While indiscriminate fungicide usage should be avoided, in general, seed lots with germination percentages lower than the established "seed standards" should be treated, but only if they reach the recommended "seed standards" following treatment. When seed shortage is a problem then all lots should be treated. In addition, when it is believed that the present inoculum level in the soil should be reduced, all seed lots, irrespective of germination percentages should be treated. Seed treatment avoids introduction of additional inoculum into the soil and reduces the inoculum already present in the soil around the seed.

A third approach, taking into consideration local results and the prices of seed dressing fungicides, is to allow a 20% seed infection limit (IAPAR 1980).

Cultural practices
Crop rotation serves as a major management practice for lowering disease levels coming from inoculum generated in

the following situations: heavily-infested soil, intermediate hosts, and saprophytic growth of the pathogen in crop residues. Soil infestation is also augmented annually by harvesting, a process causing dispersal of clouds of conidia.

Spraying schedule

At low levels, spot blotch can be controlled by chemical applications. Success of chemical control is dependent upon a well established "spraying schedule scheme" that takes into consideration, among other aspects, a threshold level for application.

Such a spraying schedule has been used for more than 10 years and has helped to reduce the number of fungicide applications and at the same time has increased their efficiency in economically managing the disease at low levels. For Brazilian conditions, a threshold level for seed treatment is 20% infection; for leaf infection, it is a "trace" at the initiation of the crop cycle. By using such threshold levels, the disease can be kept at low levels, i.e. less than 50% of the leaf area infected at the soft dough stage. The first application at the beginning of an epidemic is indispensable. After the soft

Table 2. Average percentage of leaf area infected mainly due to spot blotch and tan spot in some wheat varieties in Paraná, Brazil, during 1985-1989.

Variety/cross and soil type	Average percentage of leaf area infected at the soft dough stage/year[a]					Overall Average
	1985	1986	1987	1988	1989	
Soils without Aluminum						
Taquari (KVZ/CIANO 67/PJ= Hoopoe'S')	15	23	37	23	10	22
Caeté (JUPATECO/BLUEJAY'S')	18	22	29	18	19	21
Tapejara (Cross unknown)	15	24	22	20	10	18
Igapó (KVZ/BUHO'S'//KAL/BB)	16	20	31	11	13	18
Batuira (KEA'S')	14	27	23	18	6	18
Cacatu (BLUEJAY'S'/JUPATECO)	16	19	29	13	9	17
Pirata (ALD'S'/CNT 7//PF70354/3/ PAT 24/BB/KAL)	16	16	24	13	9	16
Soils with Aluminum						
BR 23 (CC/ALD'S'/3/IAS 54-20/ COP//CNT 8)	-	28	33	11	21	21
BR 28 (IAS 55/PF70553)	-	18	34	10	17	20
Maringá (FRONTANA/KENYA 58//PG 1)	11	20	36	10	19	19
BR 8 (IAC 20/TOROPI//PF 70100)	10	17	35	11	15	18
CEP 11 (FF 6868'2/HADDEN)	6	18	37	8	12	16
CEP 14 (PEL 72380/ARTHUR 71)	8	11	26	8	22	15

[a] Average of 8-32 experiments conducted per variety per year in eight different locations, with exception of BR 23 and BR 28, where in 1985 these two varieties were included only in four experiments. Highest disease ratings between 30-50% and rarely over 70% depending on the year. Source: L.A.C. Campos, IAPAR.

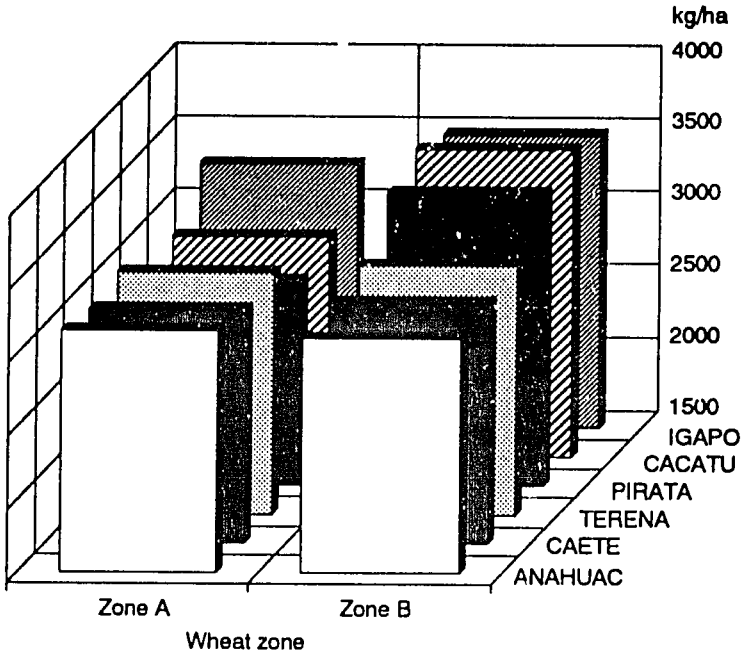

Figure 2. Average yields of some wheat varieties obtained in 8 to 47 experiments per variety per year conducted during the 1985-89 period in soils without aluminum in two major wheat zones of Paraná, Brazil. Source: L.A.C. Campos, IAPAR.

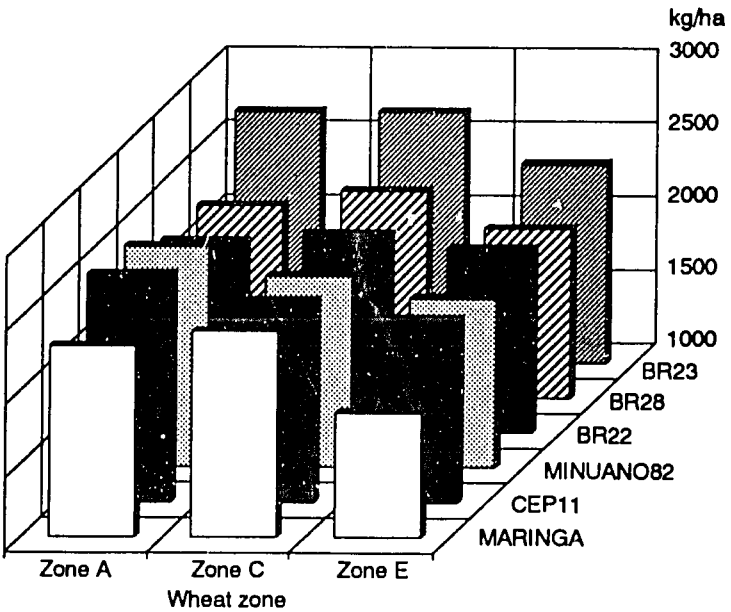

Figure 3. Average yields of some wheat varieties obtained in 4 to 82 experiments per variety per year conducted during the 1985-89 period in soils without aluminum in three major wheat zones of Paraná, Brazil. Source: L.A.C. Campos, IAPAR.

dough stage, fungicide applications do not economically improve yield (Mehta et al. 1978). Details of the spraying schedule are already reported (Mehta and Igarashi 1985) and undoubtedly require modification for ear diseases and/or seed multiplication fields, with respect to threshold levels. Threshold levels require determination on a regional basis with careful consideration of several aspects (Zadoks 1985).

Genetic Protection against *Cochliobolus sativus* in Wheat

Breeding for resistance commands high priority, although the level of resistance in commercial spring bread wheat is currently rather low. The pathogen has a broad host range among graminaceous species. In wheat, it can attack basal parts, leaves, nodes, heads, and seeds, producing different symptoms and consequent damage to the reproductive parts. Severe infection of leaf blotch on wheat can cause destruction of tissue which, during decomposition, promotes profuse production of conidia. Pathogenicity is associated with the production of helminthosporal (Ludwig 1957) and victoxine toxins (Pringle 1976).

Certain wheat accessions express lower disease severity, i.e. restricted lesion size and reduced conidial production. However, during severe epidemics most accessions succumb to the pathogen resulting in high yield losses (Mehta 1985). Breeding for resistance has been hampered by a scarcity of good resistance sources in agronomic germplasm.

Differences in resistance to both root and leaf blotches exist among wheat varieties. Larson and Atkinson (1982) reported that resistance to root rot is controlled by a single recessive gene. Adlakha et al. (1984) reported simple inheritance of resistance to leaf blotch disease. More complex inheritance was recorded for varieties showing moderate resistance (De Pauw et al. 1984).

According to Johnson and Lupton (1987), even though root and leaf blotch disease are widespread and severe, progress in breeding resistant varieties has not been rapid, probably because resistance to other diseases such as the rusts has taken priority.

Dhaliwal et al. (1986) have found very little resistance to leaf blotch in the germplasm of wild wheats and *Aegilops* spp. While none of the *Triticum uratum* accessions are resistant, *Aegilops squarrosa*, other D genome species, and some S genome *Aegilops* spp., except *Ag. speltoides*, possess resistance.

Wheat plants—regenerated from callus lines surviving exposure to purified culture filtrate produced by *C. sativus*—were less susceptible (Chawla and Wenzel 1987). Of 56 regenerated calli of the wheat cultivars Atys and Pitic 62, nine regenerated seedlings expressed resistance to *C. sativus*. Neither insensitive nor resistant reactions were observed in 150 randomly selected plants not subjected to the toxic culture filtrate.

Three different approaches are currently being followed to enhance genetic protection in wheat to *C. sativus*:

- Screening of wild emmer wheat *Triticum dicoccoides* Koernicke to Israeli and German isolates of *C. sativus*.
- Production and evaluation of wheat plants regenerated from calli derived from agronomic wheat cultivars.
- Incorporation of multi-resistance sources into agronomic wheat through crossing.

Wild emmer wheat

Seedlings of wild emmer wheat (*T. dicoccoides*) collected in Israel (by E. Nevo, Haifa University) were each inoculated either as detached leaves with a 10-μl aliquot of *C. sativus* isolate ISR02 or as 10-day-old seedlings with 10 ml of a 10^4 spores/ml suspension per tray, 20 plants/tray. Both detached leaves, incubated in Petri dishes on water agar, and whole plants were placed at 18°C with a daily 12-hour photoperiod. Percentage lesion area was assessed 4 to 5 days after inoculation.

Wild emmer accessions expressed diverse responses to *C. sativus* isolates applied to detached leaves or to plants (Table 3). Differences were found in the response to the two isolates, and a rather low linear correlation was found between detached leaves and whole plants inoculated with isolate ISR02 (R^2=0.41*) in this experiment.

The level of disease (measured as percentage of lesion area) was significantly lower in accessions collected in northern Israel (Mount Hermon and Quazrin) than in collections from the south.

Table 3. Response of wild emmer accessions (*Triticum dicoccoides*)[a] to isolate ISR02 and FRG22 of *Cochliobolus sativus*.

Source		Leaf segment[b] mean lesion coverage (%) ISR02	FRG22	Whole plant[c] mean lesion coverage (%) ISR02
Mt. Hermon	G-1	1.9	2.8	9.0
	G-3	12.3	3.2	7.9
	G-22	17.0	3.3	0.5
	G-56	4.4	7.2	16.5
	G-59	12.0	5.0	10.0
	G-60	6.9	5.4	1.1
Quazrin	A-43	18.5	10.7	5.5
	A-54	11.5	2.5	1.6
	A-64	25.0	15.5	9.5
	A-79	21.0	11.0	5.0
Yehudia	8-19	15.5	6.7	12.5
	8-37	17.0	7.8	14.0
Rosh Pina	C-42	11.0	12.5	26.0
Tabigha	H-5	14.5	16.5	7.0
	H-7	9.1	18.0	11.5
	H-15	20.0	13.5	22.5
	H-54	13.1	11.9	3.5
Kochav Hashahar	K-41	26.0	18.7	22.2
Beit Meir	F-88	24.5	24.0	39.0
Sanhedria	E-4	15.5	25.0	29.5
	E-6	8.0	19.0	55.0
	E-18	20.0	25.0	2.6
Taiyba	J-09	29.5	26.0	44.0
	J-28	16.0	17.0	35.0
Bat Shlomo	I-4	19.5	18.5	5.0
	I-27	14.0	19.0	22.0
	I-36	16.2	8.7	18.5
	I-38	16.0	14.5	9.0
	I-42	16.9	21.2	17.5
Ya'abed	24-2	10.8	19.1	5.5
	24-14	15.0	12.5	31.0
	24-18	15.5	15.0	34.0
	24-23	18.5	15.0	47.0
	24-48	19.5	16.0	11.5
Shafir (check)		21.1	10.1	14.0

[a] Seeds collected by E. Nevo, Haifa University, Israel.
[b] Detached leaves (2 cm) inoculated with 10 μl of 10^4 spores/ml.
[c] Wheat seedlings inoculated with 10^4 spores/ml.

Somaclonal variation

Two Israeli spring bread wheat cultivars, Bet Hashita and Shafir, both susceptible to *C. sativus* were grown in the greenhouse, and caryopses 14-16 days after fertilization were collected and surface-sterilized. The embryos were excised aseptically and placed, scutellum up, on the surface of the initial culture medium (Murashige and Skoog [MS] 1962) which contained 4.709 g/L MS nutrient medium (Flow Lab), 2% sucrose, up to 2 mg 2,4-Dichlorophenoxy acetic acid (2,4-D)/L, 3% polyethylene glycol (PEG)-600, and 1.25% agar. Cultures were maintained at 27°C with continuous lighting and transferred to fresh media every 4 to 6 weeks. Shoot regeneration was induced by transfer of calli to the above media lacking 2,4-D.

Regenerated plants were inoculated with *C. sativus* isolate ISR02 by using the detached leaf procedure and the seedling procedure. Variation in somaclones produced via somatic embryogenesis from scutellar callus was followed through several generations. The frequency of clones expressing low lesion coverage (0-10%) for Bet Hashita was 30% and 18.3% for Shafir (Table 4). Plants produced from Shafir clones expressing low lesion coverage from T-33 failed to maintain the low coverage in the next generation (SC_3) whereas clones of T-76 from Shafir, which expressed rather low variation in SC_2, resulted in rather variable reactions (SC_3) to isolate ISR02 (Table 5).

Clones expressing different levels of response to the second leaf were reinoculated in the fifth leaf with the same isolate. Clones expressing low coverage (T-76-2) maintained the low disease coverage. Most regenerated plants selected for low disease coverage expressed lower mean disease coverage than the nonregenerated susceptible Shafir (Table 6).

Differential Interactions

Identification of races in Brazil (Mehta 1981) and reports of a biotrophic phase during infection of cereal leaves (Dehne and Oerke 1985) support the idea that physiologic specialization exists in *C. sativus* populations regionally. The instability of germplasm resistance to spot blotch in different parts of the world, a fact reported for wheat bred in Mexico and grown in Zambia (Raemaekers 1985), resulted in the decision to monitor isolate populations on a global scale, by analyzing pathogenicity. Resistance breeding schemes need to be based on the knowledge of virulence frequencies occurring worldwide.

Table 4. Seedling response of Bet Hashita and Shafir in SC_2 generation to *Cochliobolus sativus* isolate ISR02 (10^4 spores/ml).

Response class (lesion coverage)	Frequency (%)	Lesion coverage (Mean)	Range
Bet Hashita			
0-10	30.0	3.4	0.0-10.0
11-20	30.0	16.9	11.1-20.0
>20	40.0	32.9	21.0-57.8
Shafir			
0-10	18.3	3.9	0.0-10.0
11-20	13.3	16.5	11.4-20.0
>20	67.5	47.7	21.0-96.7
Shafir (control)		51.0	
Bet Hashita (control)		40.0	

Several hundred infested samples carrying spot blotch and other leaf blotching diseases were collected since 1987 in disease "hot spot" locations. After incubation and identification of *C. sativus*, monoconidial isolates were produced and ultimately conidia were stored on filter paper disks at 5°C. Infected material consisted primarily of dry cereal leaves, occasionally of seed and, in very rare cases, of haulm bases or even soil. *C. sativus* conidia were identified in 400 samples collected from 24 countries.

To verify differential interactions of *C. sativus* isolates on wheat, a differential set of varieties had to be established. A large number of bread and durum wheat and triticale genotypes from diverse sources were screened at early plant stages (GS12-GS13) for their suitability as *C. sativus* differentials, but the chosen set comprised only wheat genotypes. These genotypes (Table 7) are known to show a considerable level of resistance to field infection by *C. sativus* populations in Brazil. As additional genetic sources were screened, it became obvious that wheat wide cross hybrids incorporated considerable levels of resistance to test isolates. Consequently, one wheat/ *Agropyron curvifolium* hybrid line was selected as a differential. Several more resistant genotypes were detected among breeders' material of different origin.

For screening experiments 206 isolates from 24 countries were chosen. Isolates from all regions and locations of each country were assessed. Isolates from the same country were tested together in one or several experiments. For interaction studies with a large number of isolates, a laboratory testing system was established. Detached leaf segments of plants at GS12-GS13 were put on benzimidazole (30 ppm) containing water agar in plastic dishes. Segments were drop-inoculated with conidial suspensions of $2x10^4$ spore/ml and incubated at 21°C with a light period of 12 hours. Infection was assessed 6 or 7 days after inoculation.

Table 5. Seedling response of Shafir regenerants to *Cochliobolus sativus* isolate ISR02 (10^4 spores/ml).

Accession		Lesion coverage (%) ± SD
Shafir		51.0 ± 35.1
T-33	SC_2	0.1 ± 0.0
T-33 - 1A	SC_3	65.1 ± 20.4
- 1B	SC_3	57.6 ± 23.8
- 1C	SC_3	57.0 ± 18.9
T-76	SC_2	16.7 ± 5.0
T-76 - 2A	SC_3	25.3 ± 15.6
- 2B	SC_3	21.3 ± 15.0
- 2C	SC_3	15.7 ± 10.1
- 2D	SC_3	7.8 ± 3.2
T-76 - 3A	SC_3	37.5 ± 7.4
- 3B	SC_3	7.2 ± 7.4
- 3C	SC_3	28.8 ± 22.0
- 3D	SC_3	21.4 ± 20.5

SC_2 = 2nd generation from callus.
SC_3 = 3rd generation from callus.

Table 6. Seedling response of SC_3 Shafir regenerants to *Cochliobolus sativus* isolate ISR02 (10^4 spores/ml).

Accessions	Lesion coverage primary leaf	Lesion coverage of 5th leaf
T-76-2A	Trace	5.0 ± 0.0
T-76-2B	5.01	3.8 ± 6.5
T-76-2C	10.02	2.2 ± 11.6
T-76-2D	20.02	0.0 ± 7.1
T-76-3A	Trace	15.0 ± 5.0
T-76-3B	5.02	8.9 ± 13.4
T-76-3C	10.02	5.0 ± 9.2
T-76-3D	20.03	8.0 ± 12.5
Shafir	50.0 ± 2.5	51.0 ± 5.3

Lesion size was measured as the percentage segment area comprising chlorosis and necrosis, on a 1 to 7 quantitative scale and necrosis type was scored on a 1 to 5 qualitative scale. A split plot design was employed with three replications.

Means of lesion size scores obtained by analyses of variance allowed the selection of two very diverse isolates per country. These isolates and single isolates from other countries were assembled into a global set of 45 isolates (Table 8). Six isolates were included from Brazil owing to the importance of the disease in that country. This global set was screened in a single experiment against the *C. sativus* differential set containing 12 entries.

Interaction Analyses

Differential interactions were established during preliminary trials with national *C. sativus* isolate sets. The interaction term for Thailand isolates, for example, accounted for 1.3% of the total variance. Main factors and interaction of "varieties" (indicated as set number) and isolates were highly significant ($p<0.001$) (Table 9). Isolates from northern and northeastern Thailand, minor wheat production areas, were highly variable in pathogenicity. In contrast, isolates from other countries, such as Nepal, exhibited no interactive responses on the differential varieties (Table 10) and no significant differences between the Nepalese isolates were obtained at all. This is a reflection of their similar reaction pattern even though differences in response do exist.

The main pathogenicity study consisted of 45 selected isolates tested in two replications. Due to logistical restraints, each replication had to be split into three units which were respectively planted, inoculated, and scored on 3 consecutive days. A split plot design was employed.

Mean percentage lesion areas were significantly different between isolates, varieties, and replications, but no interactive responses occurred (Table 11). This could be attributed to the low number of replications or it could be a result of the criteria used for selection of isolates and differential varieties.

Isolates of generally high or generally low pathogenicity do not provide the scope for

Table 7. Preliminary *Cochliobolus sativus* differential set members.

Diff. set No.	Code/name	Cross	Species	Donor
1	BH1146	FRONTEIRA/MENTANA//PG1	*T. aestivum*	IAPAR
2	-	BON/YR/3/F3570//KAL/BB	*T. aestivum*	IAPAR
3	CNT 1	PF 11.100-62/BH1146	*T. aestivum*	IAPAR
4	IA 7956 (VEE'S')	-	*T. aestivum*	IAPAR
5	IA 7968 (SUNBIRD'S')	-	*T. aestivum*	IAPAR
6	IA 807	KVZ/K4500 L.A.4	*T. aestivum*	IAPAR
7	LD 7831	Unknown	*T. aestivum*	IAPAR
8	PAT 7219	S12/J 9280.67//NB/TP	*T. aestivum*	IAPAR
9	PF 7339	SON64/SKE//LR64A/IAS49	*T. aestivum*	IAPAR
10	BR 8	-	*T. aestivum*	IAPAR
11	CS/AC 4	CHINESE SPRING/ *Agropyron curvifollum*	x *Triticum*	CIMMYT
12	IAPAR 1 (Mitacoré)	IAS 50/JARAL	*T. aestivum*	IAPAR

obvious interaction. In contrast, interactive responses of isolates of intermediate pathogenicity can be easily established, as indicated by the NE-Thailand isolates. There are extreme differences in overall pathogenicity of isolates from the global selection but significances can only be established for isolates of high and low general pathogenicity (Figure 4). Differential varieties were significantly different ($p<0.05$) with respect to lesion area (Figure 5) and fell into four distinct groups. The highly susceptible standard variety IAPAR 1 (Mitacoré) had highest disease severity, whereas line IA807 (KVZ/K4500 L.A.4) ranked top among resistant genotypes.

Table 8. Selected *Cochliobolus sativus* monoconidial isolates for pathogenicity analysis on a global basis.

Country Isolate code[a]	Coll. year	Region	Location	Host[b] species	Collector
ARG01	1988		Pergamino	TA	Bekele
ARG02	1988		Pergamino	TA	Bekele
BOL01	1988		Santa Cruz	TA	Bekele
BRA010	1987	Matto Gr.Ds	Dourados	TA	Fernandez
BRA058	1987	Paraná	Prim de Maio	TA	Mehta
BRA065	1988	Paraná	Londrina	TA	Kohli
BRA075	1988	São Paulo	Assis	TA	Mehta
BRA080	1988	São Paulo	Assis	TA	Mehta
BRA111	1988		Marachai	TA	Mehta
BRD06	1988	Niedersachsen	Goettingen	TA	Mann
BUR01	1988	Shan State	Heho	TA	Mann
ETH01	1988		Sinana	TA	van Ginkel
IND11	1988	U. Pradesh	Faizabad-Mawda	TA	Tandon
IND13	1988	U. Pradesh	Faizabad	TA	Tandon
INS01	1988	West Java	Pacet-Cianjur	TA	Sudjadi-S.
INS02	1987	West Java	Pacet	TA	Sudjadi-S.
ISR02	1987		Gilat	TA	Eyal
ISR08	1986			TA	Eyal
JPN11	1988	Hokaido	Kitami	TA	Fehrmann
JPN17	1988	Hokaido	Kitami	TA	Fehrmann
MEX01	1987		Poza Rica	TA	James
MEX32	1989				CIMMYT
MWI01	1988		Ntchjsi	TA	van Ginkel
MWI02	1988		Bvumbwe	TA	van Ginkel
NPL02	1987		Kathmandu	TA	Dubin/Karki
NPL19	1989	Terai	Bhairahawa	xTA	Fehrmann
PHI28	1988	Isabela	San Mateo	TA	Hetzler
PHI31	1988	Laguna	Los Baños	TA	Hetzler
PRY03	1988		Agriex	TA	Mann
PRY06	1988		Naranjal	TA	van Beuningen
RWA01	1989		Rwerere	TA	van Ginkel
THA060	1988	N-Thailand	Phrae	TA	Hetzler
THA127	1988	Nw-Thailand	Doi Muser	TA	Hetzler
TUR01	1988		Gerze	TA	Saari
TUR02	1988		Boyabat	TD	Saari
TZA01	1988		Hanang Complex	TA	van Ginkel
VRC01	1988	Yunnan	Yuanme	TA	Chen Quiang
VRC13	1988	Heilonjiang	Honxinglong	TA	Pfeiffer
VTM01	1987	Tam Diep Distr	Ha Nam Ninh	TA	Mann
VTM04	1988	Lam Dong Prov.	Bao Loc	TA	Mann
ZAR01	1989		Fungurume	TA	van Ginkel
ZAR02	1989		Fungurume	TA	van Ginkel
ZIM01	1988		Nyanga	HV	Mtisi
ZMB01	1988	Gwembe Valley	Sinazongwe	TA	van Ginkel
ZMB02	1989		York Farm	TA	van Ginkel

[a] Three-letter code indicates country of origin.
[b] Ta = *T. aestivum*; xTA = wheat wide cross; TD = *T. durum*; HV = *H. vulgare*.

Table 9. ANOVA table of lesion percentage from a screening experiment with 13 Thai isolates and one standard highly pathogenic monoconidial *Cochliobolus sativus* isolate on 12 members of the preliminary differential set using detached leaves with a split plot design.

Source	DF	ANOVA SS	Mean square	F value	Pr>F
Corrected total	503	169073.4270			
Replication	2	3078.90161	1539.45081	22.89	0.0001
Isolate	14	75629.87943	5402.13425	24.10	0.0001
Rep*isolate	25	5604.25529	224.17021	3.33	0.0001
Set number	11	45578.45077	4143.49552	61.60	0.0001
Isolate*set number	154	19205.47436	124.71087	1.85	0.0001
Error	297	19976.4655	67.26		
R-Square		C.V.	Root MSE	MLPZ Mean	
0.881847		25.59604	8.201270	32.0411706	

Table 10. ANOVA table of lesion percentage from a screening experiment with 11 Nepalese isolates and one standard highly pathogenic monoconidial *Cochliobolus sativus* isolate on 12 members of the first preliminary differential set using detached leaves, with a split plot design.

Source	DF	ANOVA SS	Mean square	F value	Pr>F
Corrected total	431	229135.8630			
Replication	2	8383.72689	4191.86345	18.63	0.0001
Isolate	11	26131.12042	2375.55640	1.89	0.0982
Rep*isolate	22	27651.39636	1256.88165	5.59	0.0001
Set number	11	82044.21280	7458.56480	33.15	0.0001
Isolate*set number	121	25527.50500	210.97112	0.94	0.6528
Error	264	59397.9016	224.9921		
R-Square		C.V.	Root MSE	MLPZ7 mean	
0.740774		44.06746	14.99974	34.0381173	

Table 11. ANOVA table of lesion percentage from a pathogenicity analysis of 45 monoconidial *Cochliobolus sativus* isolates on 12 differential "varieties" using detached leaves, with a split plot design of two replications.

Source	DF	ANOVA SS	Mean square	F value	Pr>F
Corrected total	1079	431861.0373			
Replication	1	6356.2836	6356.2836	39.36	0.0001
Isolate	44	156401.7761	3554.5858	4.15	0.0001
Rep*isolate	44	37675.6363	856.2645	5.30	0.0001
Set number	11	85588.7652	7780.7968	48.18	0.0001
Isolate*set number	484	65906.2855	136.1700	0.84	0.9701
Error	495	79932.2906	161.4794		
R-Square		C.V.	Root MSE	MLPZ mean	
0.814912		30.97979	12.70745	41.0185274	

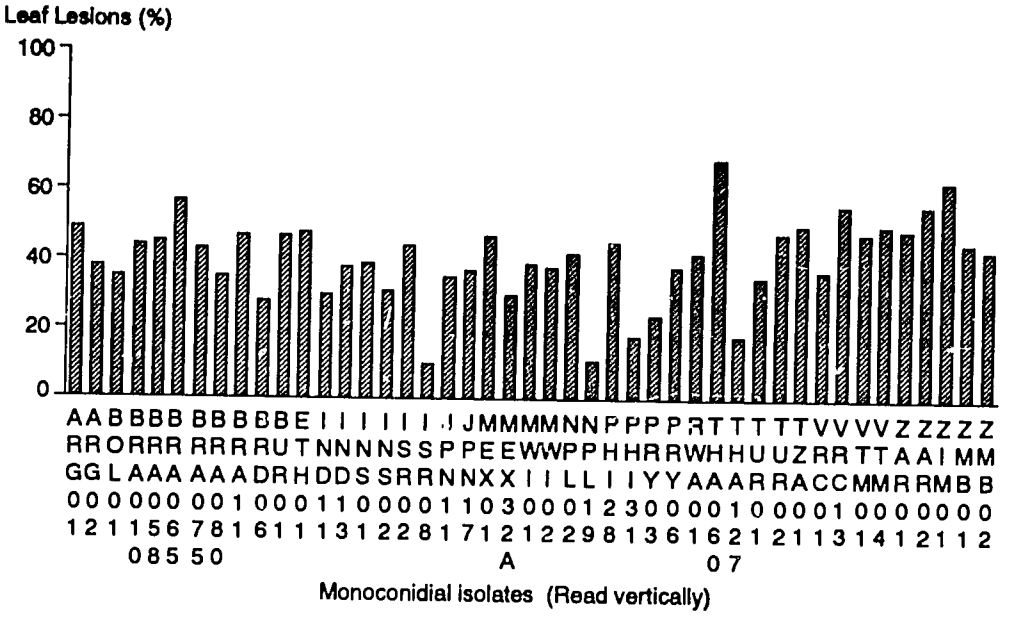

Figure 4. General pathogenicity of 45 *Cochliobolus sativus* monoconidial isolates on members of the preliminary differential set using detached leaves and parameter lesion area.

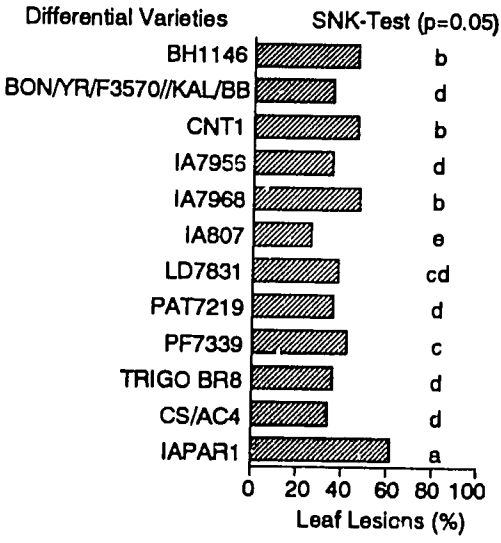

Figure 5. General susceptibility of 12 differential set members after infection of leaf segments with a global selection of *Cochliobolus sativus* monoconidial isolates. Lesion area means (n = 90) with the same letters are not significantly different (Student-Newman-Keuls Test, SNK, p<0.05).

Host responses were classified into low infection type (LIT), intermediate infection type (IT), indeterminable infection type (XIT) or high infection type (HIT). An infection response of below 20.0% mean lesion area (LIT) possibly indicates host resistance or corresponding pathogen avirulence. Intermediate infection types range between 20 and 27.5% mean lesion area. The same is true for the so-called "indeterminable" resistance type, where the mean comprises a resistance reaction in one replication contrasted by a clearly susceptible reaction in the other. High infection types were classified as mean lesion areas of above 27.5% and undoubtedly resemble a susceptible reaction. By classifying host/isolate responses in a matrix (Table 12) firstly, according to decreasing isolate pathogenicity (top to bottom), and secondly according to host susceptibility (left to right) 15 vertical pathotypes are indicated. Low infection levels occur in the minority of *C. sativus* isolates. Highly

pathogenic isolates fall into four different pathotypes. Pathotype 1 is highly pathogenic on all differentials and includes 60% of all isolates. Such pathotypes arise from all continents and from all *C. sativus* problem areas.

Table 12. Classified and sorted *Cochliobolus sativus*-wheat response matrix for resistance parameter lesion size of detached leaves.

	Test Varieties[a]												
Isolate	1	2	3	4	5	6	7	8	9	10	11	12	13
TZA06088	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
ZAM0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
BRA06588	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
ZAR0289	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
VRC1388	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
TZA0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
VTM0488	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
ZAR0189	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
ARG0188	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
VTM0187	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	2
TUR0288	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
ETH0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
BRA11188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
MEX0187	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
BUR0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
BRA05887	XIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
ZMB0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
PHI2888	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
BRA01087	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
ISR0287	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	2
ZMBO289	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
BRA07588	XIT	HIT	HIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
NPL0287	XIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
RWA0189	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
INS0188	XIT	HIT	HIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	1
MWI0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT	3
PRY0688	LIT	HIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	2
MWI0288	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	2
ARG0288	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	2
IND1388	IT	IT	LIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	4
VRC0188	IT	HIT	HIT	HIT	XIT	HIT	HIT	HIT	HIT	XIT	HIT	HIT	1
JPN1788	XIT	HIT	IT	HIT	IT	XIT	HIT	HIT	HIT	HIT	HIT	HIT	1
BRA08088	LIT	LIT	HIT	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	5
BCL0188	HIT	IT	HIT	HIT	IT	HIT	HIT	IT	HIT	HIT	HIT	HIT	1
JPN1188	IT	IT	HIT	HIT	HIT	XIT	HIT	HIT	HIT	IT	HIT	HIT	1
TUR0188	XIT	LIT	HIT	HIT	IT	IT	HIT	HIT	HIT	HIT	HIT	HIT	6
INS0287	LIT	HIT	LIT	HIT	HIT	LIT	LIT	HIT	HIT	HIT	HIT	HIT	7
MEX32A89	LIT	LIT	LIT	IT	HIT	HIT	HIT	IT	HIT	XIT	HIT	HIT	8
IND1188	HIT	IT	XIT	LIT	XIT	XIT	HIT	HIT	HIT	HIT	HIT	HIT	9
BRD0688	LIT	LIT	LIT	IT	HIT	HIT	HIT	HIT	HIT	IT	IT	HIT	10
PRY0388	LIT	LIT	IT	LIT	LIT	LIT	HIT	XIT	HIT	XIT	HIT	HIT	11
THA12788	LIT	IT	LIT	LIT	LIT	IT	LIT	LIT	LIT	IT	IT	HIT	12
PHI3188	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	HIT	LIT	LIT	HIT	13
NPL1989	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	XIT	LIT	14
ISR0886	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	HIT	15
RESIS.G.[b]	14	8	8	7	5	5	5	4	3	4	2	1	

1 = IA 807, 2 = CS/AC4, 3 = BR 8, 4 = PAT 7219, 5 = BON/YR/3/F3570//KAL/BB, 6 = IA 7956, 7 = IA 7968, 8 = PF 7339, 9 = BH 1146, 10 = LD 7831, 11 = CNT 1, 12 = IAPAR 1, 13 = Pathotype.

[a] Average of two replications; lesion size groups and range: LIT = 0-20%, IT = 20.1-27.5%, XIT = 20.1-27.5%, HIT > 27.5%.

[b] Potential resistance genes.

Pathotypes 2, 3, and 4 are characterized by low infection type reactions on IA807 (e.g., isolate VTM0187), LD7831 (MWI0188), and BR 8 (IND1388), respectively. Pathotypes 5 to 13 incorporate up to 11 low infection type responses and include differential interactions, as demonstrated by the reaction patterns of isolates INS0287 (Indonesia) and MEX32A89 (Mexico) on genotypes CS/AC4, IA7956, and IA7968. Pathotype 2 comprises five isolates and pathotypes 3 to 15 each comprise only one. Sorting of genotypes according to a decreasing number of corresponding resistance responses/"genes" demonstrates the superiority of differential "variety" IA807, which may possess at least 14 potential resistance genes. The wheat wide cross hybrid with *Agropyron curvifolium* (CS/AC4) possesses eight potential genes, as does wheat BR 8. However, the two are genetically different, the first being resistant to isolates BRA08088 and TUR0188, resistance features not present in BR 8. The other differentials exhibit few effective resistance responses, with the exception of PAT7219, still a preferable resistance source, with its seven effective potential genes. A classified but unsorted reaction matrix portrays variability of isolates within countries (Table 13). Differential interaction of Malawi (MWI) isolates occurs on IA807 and LD7831.

Vertical pathotype designations are only undertaken for LIT and HIT responses, with intermediate types being included with HIT responses. True intermediate reactions do occur, but often the intermediate response may reflect a contradictory result between first and second replications. In such cases, the low infection results must be considered as experimental "escapes" rather than resistance responses until further experiments can be undertaken. XITs are therefore included as HITs. It must be emphasized that the infection type groupings are artificial with cut-off points being derived from experimental experience. When improved parameters for characterization of wheat spot blotch interaction on a physiological and genetic basis are determined, cut-off levels will be refined and infection types occurring in this pathosystem substantiated.

Conclusions

Fungicides do not provide sufficient protection against spot blotch, particularly in the case of severe epidemics. Resistance to *C. sativus* remains disturbingly low among commercial wheat cultivars and it is likely to be a combination of factors and not just to a disproportional allocation of attention as claimed by Johnson and Lupton (1987).

The pathogen is associated with both root and foliar disease and there is no conclusive evidence that, by selection for resistance to one form (e.g., common root rot), one will also select for resistance to the other. In some regions, the incidence of one form is higher than the other, as both are greatly influenced by environmental conditions. *Cochiobolus sativus* is generally a rather aggressive pathogen causing necrotic lesions on leaves 3 to 4 days after inoculation, which may coalesce several days later depending on the resistance level of the genotype. Host response to artificial inoculation is highly correlated to spore concentration (Mehta 1981). Therefore, it is probable that differences in host response expressed under low spore concentrations (e.g., 10^4 spores/ml) may not be maintained under high spore concentrations or with severe epidemics.

Differences in pathogenicity of isolates may contribute to the slow progress in breeding for disease resistance. Wheat cultivars expressing a moderate level of resistance in Brazil (e.g., BH1146) have

not maintained their resistance upon exposure to a wide pathogenicity spectrum. Differences in isolate pathogenicity on a global basis have been established with 15 pathotypes being identified according to resistance reactions of a 12-member differential set.

Table 13. Classified *Cochliobolus sativus*-wheat response matrix for parameter lesion size of detached leaves.

	Test Varieties[a]												
Isolate	1	2	3	4	5	6	7	8	9	10	11	12	13[b]
ARG0188	HIT	HIT	HIT	HIT	HIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ARG0288	HIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
BOL0188	HIT	IT	HIT	HIT	HIT	HIT	HIT	HIT	IT	HIT	IT	HIT	HIT
BRA01087	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
BRA05887	HIT	HIT	HIT	HIT	HIT	XIT	HIT	HIT	HIT	HIT	IT	HIT	HIT
BRA06588	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
BRA07588	HIT	HIT	HIT	HIT	HIT	XIT	HIT	IT	HIT	HIT	HIT	HIT	HIT
BRA08088	HIT	HIT	HIT	HIT	HIT	LIT	HIT	LIT	HIT	HIT	LIT	HIT	HIT
BRA11188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
BRD0688	HIT	HIT	IT	HIT	HIT	LIT	IT	IT	HIT	LIT	LIT	HIT	HIT
BUR0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ETH0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
IND1188	HIT	XIT	HIT	XIT	HIT	HIT	HIT	LIT	HIT	XIT	IT	HIT	HIT
IND1388	HIT	HIT	HIT	HIT	HIT	IT	HIT	IT	HIT	LIT	IT	HIT	HIT
INS0188	HIT	HIT	HIT	HIT	HIT	XIT	HIT	IT	HIT	HIT	HIT	HIT	HIT
INS0287	HIT	HIT	HIT	LIT	LIT	LIT	HIT	HIT	HIT	LIT	HIT	HIT	HIT
ISR0287	HIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ISR0886	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	HIT	LIT
JPN1188	HIT	HIT	HIT	XIT	HIT	IT	IT	HIT	HIT	HIT	IT	HIT	HIT
JPN1788	HIT	IT	HIT	XIT	HIT	XIT	HIT	HIT	HIT	IT	HIT	HIT	HIT
MEX0187	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
MEX32A89	HIT	HIT	HIT	HIT	HIT	LIT	XIT	IT	IT	LIT	LIT	HIT	HIT
MWI0188	HIT	HIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT	HIT	HIT	HIT	HIT
MWI0288	HIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
NPL0287	HIT	HIT	HIT	HIT	HIT	XIT	HIT	HIT	HIT	HIT	IT	HIT	HIT
NPL1989	LIT	LIT	XIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT
PHI2888	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
PHI3188	HIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	LIT	HIT	LIT
PRY0388	HIT	LIT	HIT	LIT	HIT	LIT	XIT	LIT	XIT	IT	LIT	HIT	IT
PRY0688	HIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT	HIT	IT	HIT	HIT	HIT
RWA0189	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
THA06088	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
THA12788	LIT	LIT	IT	IT	LIT	LIT	IT	LIT	LIT	LIT	IT	HIT	LIT
TUR0188	HIT	IT	HIT	IT	HIT	XIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT
TUR0288	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
TZA0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
VRC0188	HIT	XIT	HIT	HIT	HIT	IT	XIT	HIT	HIT	HIT	HIT	HIT	HIT
VRC1388	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
VTM0187	HIT	HIT	HIT	HIT	HIT	LIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
VTM0488	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ZAR0189	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ZAR0289	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ZIM0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ZMB0188	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT
ZMB0289	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT	HIT

1 = BH 1146, 2 = BON/YR/3/F3570//KAL/BB, 3 = CNT 1, 4 = IA 7956, 5 = IA 7968, 6 = IA 807, 7 = LD 7831, 8 = PAT 7219, 9 = PF 7339, 10 = BR 8, 11 = CS/AC4, 12 = IAPAR 1, 13 = All.

[a] Average of two replications; lesion size groups and range: LIT = 0-20.0%, IT = 20.1-27.5%, XIT = 20.1-27.5%, HIT > 27.5%.

[b] General pathogenicity.

Significant interactions between isolates and differential "varieties" have been observed within and between certain regions. The interaction term reaches 1.3% of total variance in the case of a Thailand isolate set. Certain varieties express resistance to isolates from wide geographical origins. The best resistance source is line IA807 (KVZ/K4500 L.A.4).The same has been shown by van Silfhout et al. (1989) who found this line to be resistant to all 48 *Septoria tritici* Rob. ex Desm. isolates used in an international screening of virulence factors of that pathogen.

The utilization of alien germplasm in breeding for resistance has resulted in variable conclusions. Although Dhaliwal et al. (1986) have found little resistance in wild wheats and *Aegilops* spp., wild emmer accessions collected in Israel show a promising level of seedling protection to leaf blotch and should be subjected to wide pathogenicity screening. The expression of low severity in crosses with *Agropyron curvifolium* (Hetzler; Gilchrist, unpublished) under both field and controlled inoculations indicates that alien germplasm should be exploited. The wheat wide cross hybrid with *Agropyron curvifolium* proved to be a good resistance source, interacting with isolates differently than the resistant wheat genotypes.

Identified sources of resistance may differ in the type of protection they confer. Accumulation of resistance sources could provide adequate and stable resistance in agronomic wheat. Employment of new approaches to wheat improvement may provide an additional avenue in increasing genetic diversity (Liang and McHughen 1987). Somaclonal variation obtained either by exposure to a selectable pressure (toxins) or without exposure have resulted in clones with elevated levels of resistance (Chawla and Wenzel 1987). The utilization of this variation will depend on its general stability and on the magnitude of other changes induced by the *in vitro* culturing.

To determine if isolate pathogenicity is different it would be recommended to screen a preliminary differential set of varieties at several "hot spot" locations (perhaps 30 to 40) worldwide. Identified virulence factors should be used in studies of inheritance of resistance for the ultimate aim of incorporating multigenic resistance into new varieties.

The effects of tillage practices and crop rotation systems on the epidemiology of spot blotch require further investigation. The occurrence and pathogenicity of tan spot and its contribution to yield loss must also be established as should studies on the global pathogenicity of tan spot isolates.

Field experiments at "hot spot" locations will be useful to assess of new varieties so as to quantify the progress achieved in breeding for resistance to spot blotch.

Acknowledgments

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Resumen

El tizón foliar del trigo causado por Cochliobolus sativus *Ito y Kuribay desencadena graves epifitias en países tropicales de Africa, Asia y América del Sur. Se estima que las pérdidas de rendimiento llegan hasta el 87% en las variedades muy susceptibles. Se logra el control mediante el manejo integrado y las investigaciones actuales intentan incorporar la resistencia del huésped. Se seleccionan cruzas amplias de trigo con accesiones de* Agropyron *y escandia silvestre como fuentes de resistencia. Se ha encontrado variación somaclonal en la resistencia en plantas regeneradas a partir del cultivo de callos. El lento progreso del mejoramiento para obtener resistencia es resultado de una combinación de factores, que incluyen los bajos niveles de resistencia de los trigos de primavera comerciales y el amplio espectro de patogenicidad de los aislamientos de* C. sativus. *Los estudios sobre la patogenicidad efectuados con una colección mundial de aislamientos monoconidiales de* C. sativus *en un conjunto diferencial de variedades y líneas de trigo, usando pruebas con hojas desprendidas, reveló la existencia de 15 patotipos. En varias colecciones nacionales de aislamientos, se calculó que 1-2% de la varianza obedece a la interacción y se cree que en el sistema patógeno operan varios genes de la virulencia. Estos resultados indican que es necesario vigilar a nivel mundial la situación de la virulencia en localidades con una prevalencia elevada de la enfermedad, lo cual facilitará la realización de estudios sobre la herencia de la resistencia al tizón foliar.*

Integrated Disease Management—The Changing Concepts of Controlling Head Blight and Spot Blotch

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Abstract

*Head blight (*Gibberella zeae*) can infect wheat in all humid and warm areas where the crop is grown. Grain losses in the Planalto Médio region of Rio Grande do Sul, Brazil, averaged 103 kg/ha in a 6-year period. The life cycle of this pathogen is described. The main sources of inoculum for wheat infection are senesced stems of wild and weed grasses which the fungus colonizes saprophytically and where perithecia are abundantly produced. This ensures the presence of inoculum in the form of ascospores in the air all year, especially during wheat flowering. Disease outbreaks depend especially on weather conditions. However, the effects of duration of spike wetness and temperature have not yet been fully determined. Main control measures should be based on cultivar tolerance (rate of rachis colonization) or escape (avoiding caught anthers). Efficient control of this disease by crop rotation or fungicides would be very difficult to achieve.*

*Spot blotch (*Bipolaris sorokiniana*) is one of the most important diseases in the warm and wet areas where wheat is grown. Knowledge of its life cycle will help in providing recommendations for more efficient control. Main sources of inoculum are infected seeds, infected residues, soil having free dormant conidia, and secondary hosts. Control measures should concentrate on reducing the fungal inoculum by the following methods: 1) make available to farmers only seeds with a low level of infection and treated with efficient chemicals, 2) control the pathogen in crop residues through crop rotation with nonsusceptible plant species for at least 2 winters, 3) eliminate the secondary hosts as much as possible, and 4) breed for tolerance to the foliar phase of the disease.*

Head Blight of Wheat

Epidemics of head blight of wheat occur sporadically in all humid and warm regions of the world where wheat is grown (Arthur 1891, Dickson 1956, Sutton 1982, Wiese 1977). Work carried out in the State of Rio Grande do Sul, Brazil (Reis 1986a), over 6 years showed wheat grain losses up to 14% (Table 1).

Life cycle

The hosts of *Gibberella zeae* Petch (anamorph *Fusarium graminearum*) that are of major economic importance in Brazil include wheat, barley, triticale, maize, and sorghum. Figure 1 shows the life cycle of the pathogen in winter cereals. When wheat is harvested with a combine, the cleaning mechanism leaves the shrunken, infected kernels on top of the soil with the crop residues. More efficient combine cleaning will lower the percentage of infected seed collected and even more infected kernels will be returned to the soil surface. Seed cleaning machines and gravity tables in seed processing plants will remove still more of the light, infected grains. Hence, in quality seed, the percentage of infected kernels is very low. Thus one may infer that, although present, *G. zeae* is not an important pathogen associated with commercial seed under Brazilian conditions. In any event, infected seeds are not important in the continuity of this

Table 1. Wheat yield losses caused by head infection of *Gibberella zeae* determined in Passo Fundo, Rio Grande do Sul, 684 masl.

Year	Cultivar or line	Infected spikes (%)	Yield potential (kg/ha)	Losses kg/ha	Losses (%)
1984	PF 8049	2	3.404	12	0.4
1985	Coker 762	21	2.740	123	5
	PF 8122	38	1.269	186	13
1986	PF 84264	20	2.748	85	3
	PF 84265	14	2.196	57	3
	PF 84344	10	2.227	108	5
	PF 84431	22	2.644	95	4
1987	BR 14	33	2.260	273	14
	BR 15	26	2.110	130	7
1988	BR 15	16	1.595	43	2 7
1989	BR 14	28	2.292	26	1.1

Source: Reis (1986a).

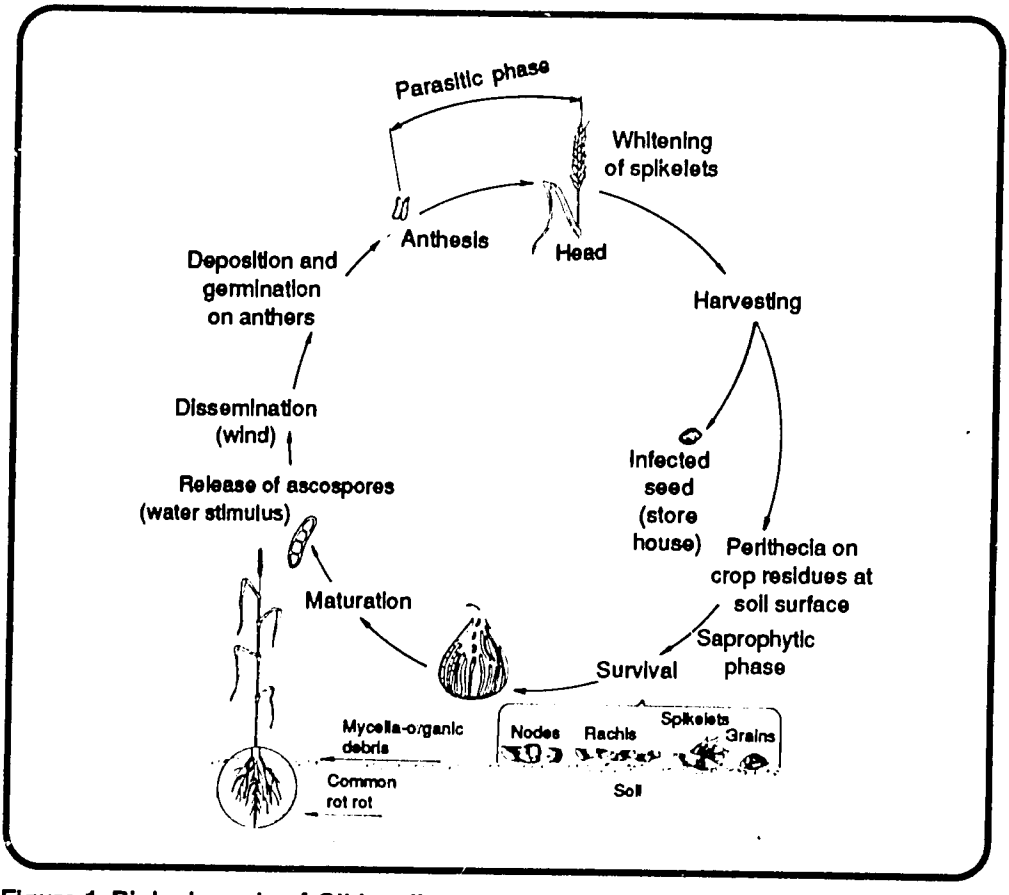

Figure 1. Biologic cycle of *Gibberella zeae* Patch in winter cereals.

fungus's life cycle, unless the infected grains are left on the soil surface. Compared with other sources of inoculum, infected seeds are the least important.

Infected wheat residues left on the soil surface contribute to some extent to the survival of the fungus. Perithecia are formed on the infected tissues left in the field after harvesting. When harvesting is done at the end of November or early December, perithecia first become visible on the third or fourth day after harvest. They mature within 10 to 15 days. In the case of winter cereals, the highest density of perithecia is formed on the spikelets containing infected kernels, rachis, and nodes. It is common to notice fruiting bodies on the glumes of infected plants before harvesting during rainy periods. The speed of perithecia formation and its maturation are functions of moisture and temperature. When infected tissues are left on the soil surface from December to January, they form and mature more rapidly than during the colder months. For example, in May or June it takes about 11 days for perithecia formation while in December-January, perithecia can be formed in 3-4 days.

Light is another important factor for perithecia formation (Tschanz et al. 1976). The perithecia form only on infected tissues that receive diffuse light (300-320 nm), and therefore perithecia will not form beneath the soil surface. Therefore, if the infected residues are buried, fruiting bodies will not develop. It may be inferred that with zero tillage, fruiting body development—and thus pathogen survival—may be enhanced (Reis 1990).

Mycelia associated with infected residues buried in the soil are the only important source of inoculum for root infection of winter cereals (Wearing and Burgess 1977). This phase of the disease is called common root rot and is caused by *Cochliobolus* and *Fusarium graminearum* (Reis 1988).

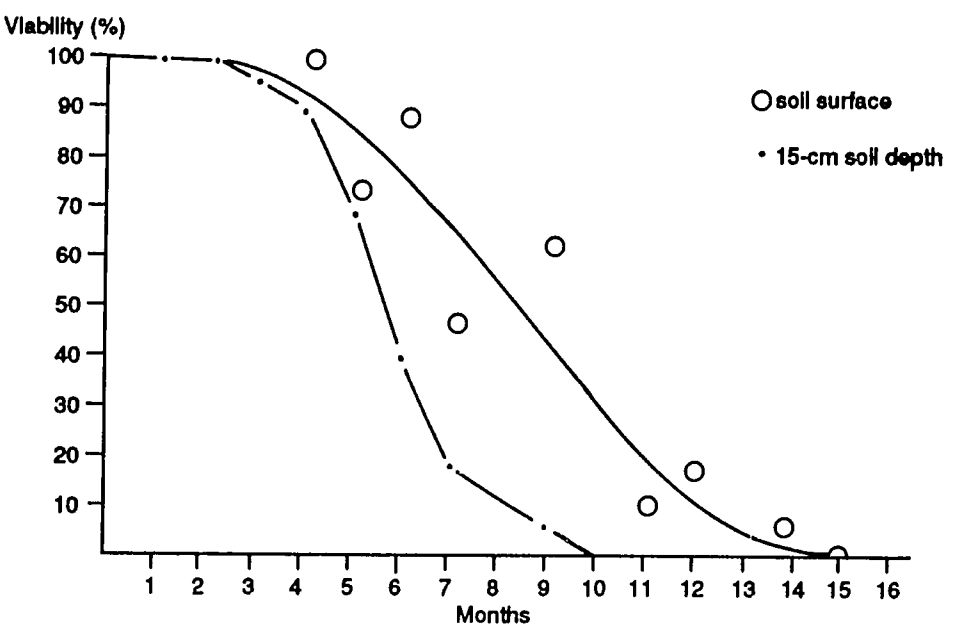

Figure 2. Survival of perithecia of *Gibberella zeae* on naturally infected maize stalks, kept at two different soil depths. Source: Reis (1986b).

The survival curves (Figures 2 and 3) of *G. zeae* perithecia in infected maize stalks left on the soil surface or buried in the soil and in naturally infected wheat kernels left on the soil surface indicate that, under field conditions, the pathogen loses its viability after complete decomposition of the substrate. This indicates that, while *G. zeae* is in its saprophytic phase, it remains viable for as long as there are nutrients available to maintain its metabolic activity. Because the residue substrate is exhausted more slowly, the fungus survives more safely during winter than during summer.

The different types of inoculum of this pathogen are mycelia, macroconidia, and ascospores and under certain conditions it produces chlamydospores, but their importance in nature is unknown (Nyvall 1970, Sitton and Cook 1981). Conidia are formed at the surface of infected tissues, but they are not suitable for wind transport. Therefore, the spread of this type of inoculum is by rain splashing over short distances. Conversely, the ascospores inside the perithecia require water as a stimulus to forcibly eject them into the air (Tschanz et al. 1975). They become airborne and may be carried for long distances by air currents. No published literature appears to describe the distance they may be taken by the wind. From the spores collected on a wheat farm near Passo Fundo, Rio Grande do Sul, Brazil, in 1984, it was found that only 1% were macronidia and 99% were ascospores (Reis 1986b).

The ascospores are always forcibly ejected into the air when the perithecia get wet. Hence, head blight is associated with rainy days during wheat flowering (anthesis). The processes of maturation and release of ascospores are cyclic, i.e., discharge after hydration and subsequent recharge. This phenomenon is dependent on free water and temperature, and

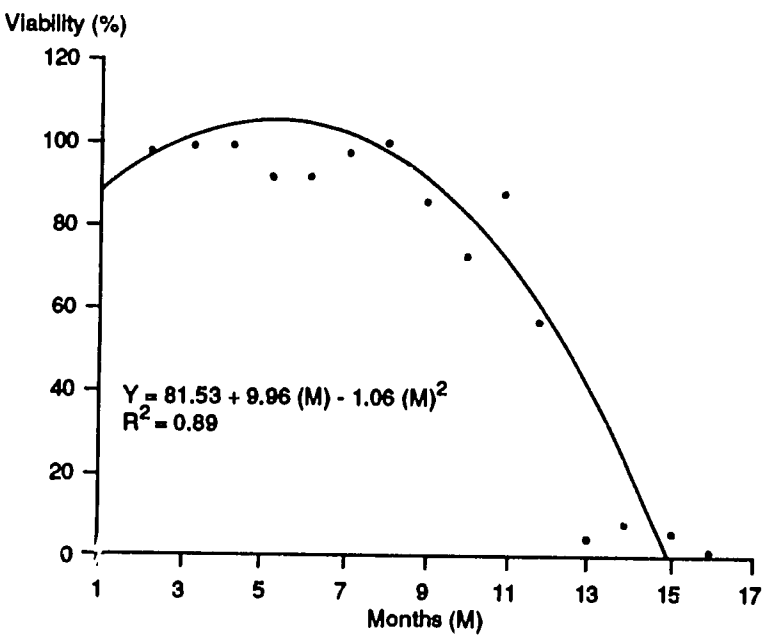

Figure 3. Survival of perithecia of *Gibberella zeae* on naturally infected wheat kernels under field conditions (Reis, in press).

continues up to the complete decomposition of crop residues that nourish the parasite.

It has been shown that, in fields under monoculture of wheat or maize, the level of inoculum in the air is high. In 1984 the maximum number of ascospores collected in an air section of 140 cm^2, in one night after 24 mm of rainfall, was 92. The density of spores is higher in the air near the soil than in the upper layers. The main sources of inoculum in southern Brazil are perithecia that form saprophytically on senesced tissues of nonhost plants (Table 2). The majority of these species are weeds in soybean crops during the summer. Plant species where perithecia are abundantly formed (Reis 1990) would be the main source of inoculum for wheat infection.

Table 2. Plant species on which perithecia of *Gibberella zeae* were found under natural conditions in southern Brazil.

Andropogon bicornis L.
Avena strigosa Schreb.
Botriochloe spp.
Brachiaria plantaginea (LK.) Hitch
Bromus catharticus Vahl.
Cortaderia selloana (Schult.) Archs. et. Graeb.
Digitaria sanguinalis (L.) Scop.
D. ciliaris (Letr.) Koel.
Lolium multiflorum L.
Oryza sativa L.
Panicum maximum Jacq.
Paspalum dilatatum Por.
P. notatum Feuegge
P. urvillei Steud.
Pennisetum clandestinum Chiov.
P. purpureum Schumach.
Sorgum halepense (L.) Pers.
S. vulgare L.

Source: Reis (1990).

Studies of the monthly fluctuation of ascospores of *G. zeae* showed that the inoculum is always present in the air (Figure 4). The infected crop residues of the host species on which perithecia are saprophytically formed guarantee the inoculum year around, most particularly during wheat anthesis. This indicates why control of the disease by including nonsusceptible species in the crop rotation is not feasible, and that control may not be achieved by trying to reduce the pathogen at the inoculum sources.

Wind-blown ascospores land on wheat anthers. This random process is dependent on the number of spores since spores not deposited on the anthers will not continue the life cycle. Those deposited on the anthers germinate in the presence of free water and temperatures of 25 to 28°C (Andersen 1948) and can rapidly penetrate the ovary.

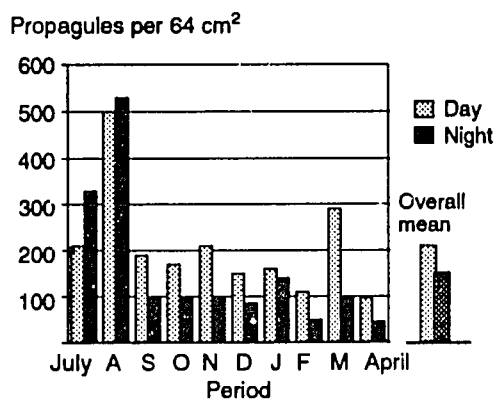

Figure 4. Propagules of *Gibberella zeae* collected with a spore trap, twice daily, from July 1983 to April 1984, in plots planted to *Trifolium subterraneum*, in Passo Fundo, RS, Brazil.

It appears that anthers can be an important infection site and that the longer the anthers remain exposed, the greater will be the possibility that they will be reached by ascospores. Thus, caught anthers may result in greater infection rates than where anthers are released (Adams 1921). In 1989, the wheat cultivar BR 14, following anthesis, had an average of nine caught anthers per spike (16 spikelets/spike). When individual anthers were examined, 4% of the released and 16% of the caught anthers were infected by *G. zeae* (Reis, unpublished data).

Control

For this peculiar disease, it is highly advisable to determine annual grain losses in each country, state, and region. Answers to the following questions should be pursued: Is this disease economically important? Is chemical control economically feasible?

Exploiting escape, tolerance, or resistance—Plant morphology and physiology should be explored for lines that do not extrude anthers or that do not leave them caught. The caught ones are likely to be very important for infection, hence lines may be screened for this character—"avoidance of caught anthers."

Rate of rachis colonization—A reduced rate of rachis colonization by the fungus may also be studied. This goal may be achieved through inoculum injection into the glumes. For these studies, Sumai 3 would be a good check variety.

Chemical control—Seed dressing is not recommended. An approach may be to spray protectant or systemic fungicides to specifically protect the caught anthers. However, what is the feasibility of chemicals reaching and effectively protecting the anthers? Fungitoxicity does exist, but deposition is difficult.

Crop rotation—This practice aimed at reducing inoculum is not feasible because the inoculum sources are very abundant and spores are transported by wind over long distances.

Spot Blotch

One of the most important foliar diseases of wheat below 24°S latitude is spot blotch caused by *Bipolaris sorokiniana* (teleomorph *Cochliobolus sativus*). Most of the results reported here were obtained in experiments conducted at Passo Fundo, Rio Grande do Sul, Brazil, located at a 28°15'S latitude and 52° 24'W longitude and an altitude of 684 masl. Hence, the control measures discussed apply only to regions having similar climatic conditions.

Life cycle

Above ground plant parts—The main source of inoculum of *B. sorokiniana* are infected seeds, infected crop residues (barley, rye, triticale, and wheat), volunteer plants, secondary hosts (summer grass weeds), and free dormant conidia in the soil. These also represent the survival mechanisms of the pathogen. From these sources, the inoculum is carried by disseminating agents (wind and rain splashes), to the green organs of wheat—the preferred tissues for parasitism.

Infected seeds are one of the most important ways for the survival of this pathogen between wheat cropping seasons (Figure 5a). The low seed water content of 12-13% maintains the pathogen in a dormant state. During the storage period, usually 6 months, the parasite may partially lose its viability (Vechiato et al. 1987). After seeding, the seeds imbibe water starting the germination and emergence processes. At this time, the fungus turns from the dormant to the vegetative state, growing from the inside to the surface of the caryopsis. Then the mycelium reaches the coleoptile and

grows up its surface reaching the tip at the soil surface, where in the presence of light, it sporulates. It may also penetrate the coleoptile and in this case the mycelium infects the emerging plumule (Figure 5e,g). When this happens, the first leaf may show one or several lesions on its surface (Reis 1981). Some times, deformations or anomalies seen in the seedlings may be due to infection. This fungus will sporulate on such necrotic tissues because *B. sorokiniana* is a necrotrophic parasite and requires light for sporulation (Spurr and Kiesling 1961). Conidia produced at the infected coleoptile tips or on necrotic lesions in the first leaves are carried by wind, under dry weather, to the leaves where secondary cycles will develop. The incidence of this disease in the early stages of wheat growth in regions where wheat was not previously grown is often observed, infected seeds being the sole source of inoculum. Transmission rate of the fungus from infected seed to the coleoptile is about 2:1 (Reis, unpublished data).

Seed health surveys in Brazil have shown that *B. sorokiniana* infection varies with growing season, cultivar, and location, and that infection levels up to 90% can be found. Seedling death may occur when highly infected seeds are sown (Figure 5f). The sporulation on the necrotic plumule will be profuse and is another way for the pathogen to reach the soil surface and to become airborne from infected seed.

Infected plant residues are another important source of inoculum on farms growing wheat in monoculture—especially where zero tillage is being used (Figure

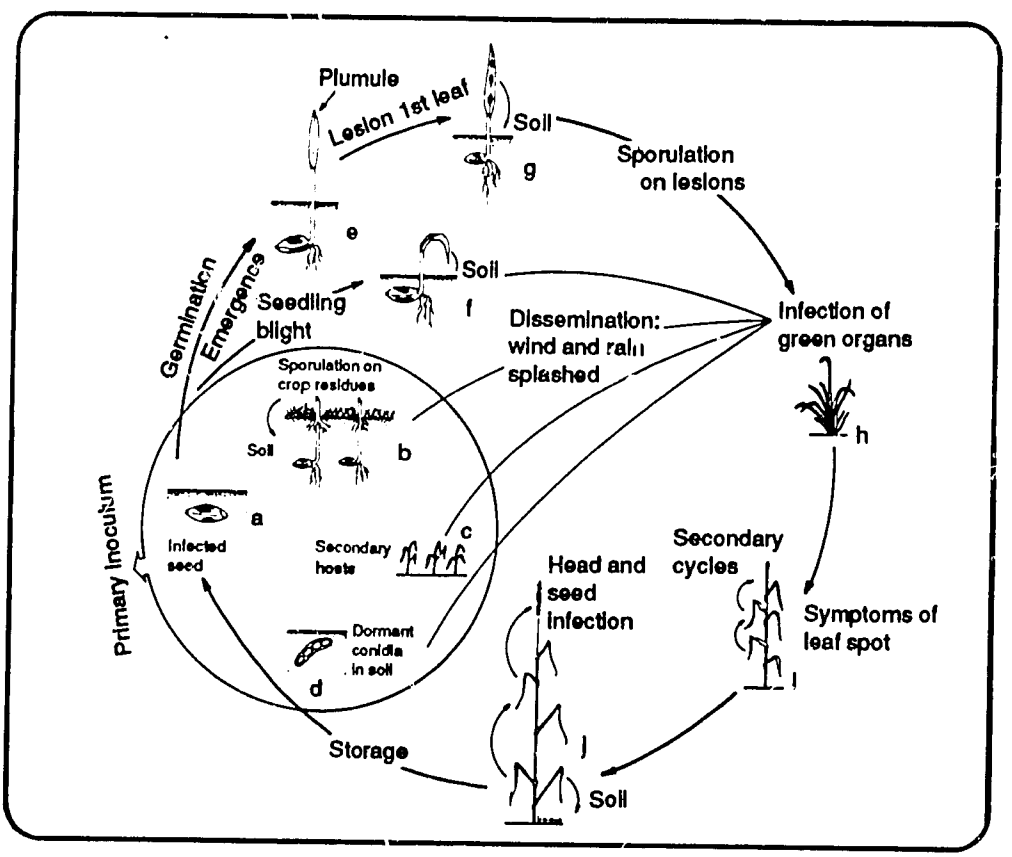

Figure 5. Life cycle of *Bipolaris sorokiniana* in above-ground plant parts of wheat.

5b). High levels of spores have been counted on such residues. Sporulation does not exist on the green tissues during the early stages of plant growth unless necrotic spots are present. Nevertheless, as soon as the necrotic lesions become visible, sporulation takes place. The rate of multiplication depends on the proportion of dead tissues, hence sporulation is at its maximum at plant maturity or close to harvest. The multiplication of the parasite continues on the residues after harvesting up to the depletion of the substrate (Reis 1984a, Reis and Abrao 1983).

B. sorokiniana does not have competitive saprophytic ability. The spores produced on infected residues are finally deposited on the soil or in the next emerging crop in the ensuing growing season (Figure 5h). The infected residues are the most important source of inoculum on which the pathogen is ideally positioned for wind or rain dissemination to the new crop. Residues of volunteer plants play the same role. *B. sorokiniana* has been isolated from leaf spots and detected on senesced tissue of some summer grass weeds (Reis 1982a, Reis et al. 1985). These plants can also be an alternative inoculum source (Figure 5c).

Dormant free conidia in the soil are another important inoculum source (Figure 5d). The origin of this inoculum is primarily infected crop residues at the soil surface and also the multiplication of the fungus in infected green plants. These spores, which can live freely in the soil for up to 37 months, may be carried by wind or rain splashes to the seedlings of the emerging crop—mainly the basal leaves closer to the soil (Reis 1984b, Reis and Baier 1983, Reis and Santos 1987, Reis and Wunsche 1984).

The conidia produced in the plumules of dead seedlings, infected crop residues, and senesced residues of secondary hosts—and those free and dormant in the soil—will cause infection in the emerging wheat crop where it will restart its parasitic phase. In infected plants, characteristic tan spots can be seen. After necrosis of the tissues and an adequate temperature and leaf wetness duration, epidemics will be built up by the secondary cycles, and as a result the upper leaves and the neighboring plants will become infected. Finally, the pathogen reaches the flag leaf, the spikes, and the seeds (Figure 5j). For a disease outbreak, it is necessary that the leaves remain wet for more than 18 hours and that the mean temperature be equal to or above 18°C (Table 3).

Ultimately, the pathogen reaches and infects the seeds, which, when harvested and placed in storage, ensures a secure way for the pathogen to survive in association with the host.

Roots—As described before, during germination and emergence, the mycelium grows from the inside of the caryopsis to

Table 3. Leaf wetness period (hours) in function of the mean temperature (°C) required for light, moderate and severe infection of *Bipolaris sorokiniana* in wheat.

Mean temperature °C	Disease severity light	moderate	severe
10	>41	-	-
15	16-38	45-74	-
20	11-13	13-15	>15
25	9-13	15-20	>21
30	8-12	14-19	>21

Disease intensity: light, 1 to 4 lesions per leaf; moderate, 5 to 9; and severe, >10. (-) severity not reached.
Source: Reis and Barcellos (1988).

its surface (Figure 6a). Finally, it reaches the coleoptile and the seminal roots which it colonizes (Figure 6b,c). Brown lesions can be seen on the coleoptile. The infecting mycelium may or may not penetrate the coleoptile wall. Lesions on the subcrown internode are easily seen when the infected coleoptile falls off. In regions where wheat is grown under low rainfall, these symptoms of common root rot are observed under field conditions. When infected seeds are sown 5 cm deep in sterilized soil, this kind of infection is easily demonstrated. Through this methodology, it may be clearly shown that one of the sources of inoculum for common root rot is the seed (Reis 1982b). During plant development under high soil moisture and high temperature, the colonization progresses and infection takes place on the crowns, secondary roots, and lower leaf sheaths. Later, the pathogen may kill the lower leaves where it sporulates abundantly. Most of these conidia are carried by rain or wind, adding to the soil inoculum (Figure 5e). This inoculum may also infect above-ground plant parts as described earlier.

The epidemiological role of the free conidia that survive in the soil through mycostasis has not yet been fully investigated.

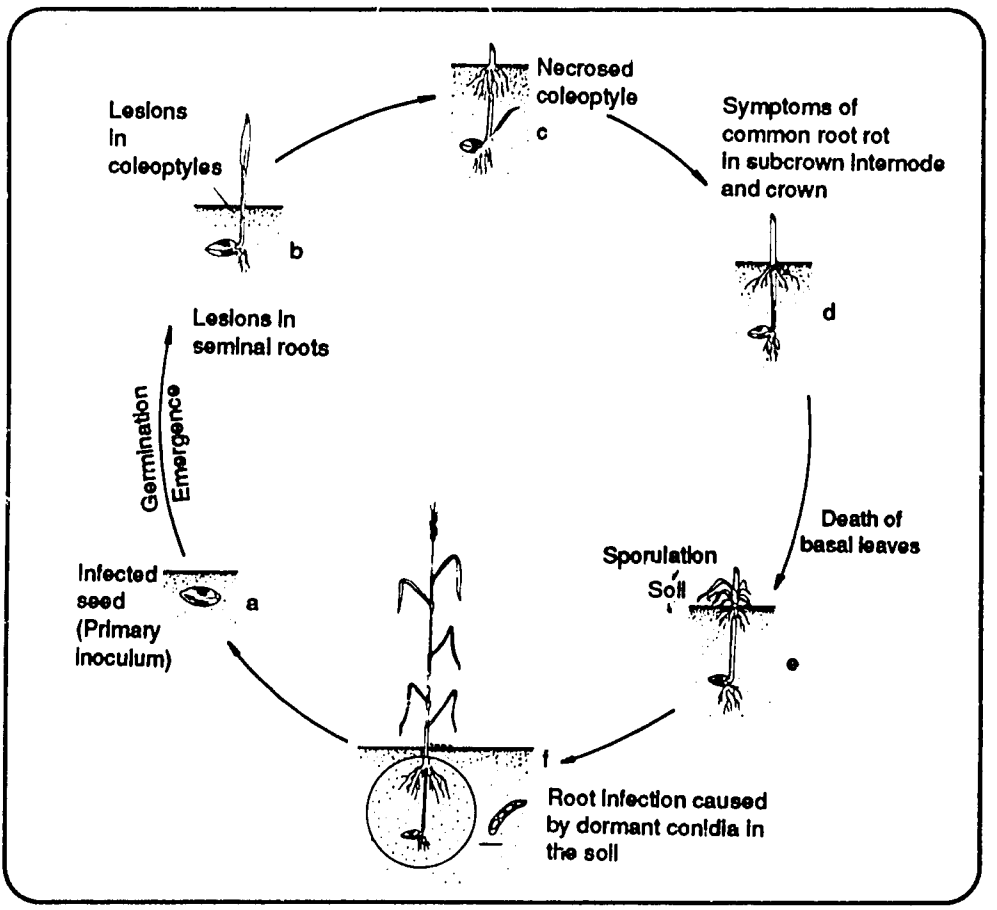

Figure 6. Biologic cycle of *Bipolaris sorokiniana* in underground plant parts of wheat.

Nevertheless, it has been shown, both in the greenhouse and in field experiments, that these spores may infect the coleoptile causing symptoms similar to those caused by seed inoculum—even causing lesions on the plumules. Thus symptoms observed in the field do not permit distinguishing whether the inoculum came from the seeds or from the soil.

Control

The basic principle involved in the control of this pathogen is reducing the population of the inoculum source. Every available measure should be used to suppress initial inoculum as much as possible.

Seeds as sources of inoculum—The transmission rate from the seed to coleoptiles is 2:1, thus only healthy seeds should be sold to farmers (Reis and Baier 1985). Experiments have shown that good control depends on the percentage of infected seed, the type of fungicide, and dosage of the chemical. Hence, only seed lots having infection lower than 30% should be treated with iprodione + thiram (250 g/100 kg of seeds) or iminoctadine (250 ml/100 kg of seeds) to achieve 100% control. Lots with infection higher than 30% should be discarded because chemical control will be inefficient (Reis, unpublished data).

Crop residues as sources of inoculum—The pathogen can be controlled on the farm through crop rotation with nonsusceptible crops over 2 winters. Crop residues are broken down after 12 to 14 months under the conditions of Rio Grande do Sul, Brazil. To terminate sporulation after harvesting, the summer crop (soybeans or maize) should be seeded conventionally so that infected wheat residue is buried. The wheat crops may be drilled directly.

Free conidia in the soil as sources of inoculum—Conidia may survive freely in the soil for up to 37 months. Thus, if a two-winter rotation schedule is followed, it will be 30 months until the seeding of the next wheat crop. This time span will reduce soil inoculum density below the numerical threshold (Reis, unpublished data).

Volunteer and secondary hosts as sources of inoculum—Such plants should be controlled in the soybean or maize crop phase of the rotation.

Slowing the epidemic rate through rational use of proper foliar fungicides—The spraying of fungicide to control *B. sorokiniana* in the foliage should be based on a dynamic, practical objective and economic criteria. Research in Brazil over 4 years (Reis, unpublished data) showed that propicorazole in triticale (125 g ai/ha) should be applied at flowering only when the disease incidence reaches the 10% level on flag leaves. Regression analysis showed that each 1% increase of incidence on the flag leaf reduces triticale yield by 18 kg/ha. Application costs are covered with 180 kg grain/ha. It is expected that, by using the integrated control measures discussed here, the level of incidence may not reach 10% and therefore fungicide spray may be unnecessary, thus keeping production costs low. The importance of controlling this pathogen at the inoculum source is easily illustrated by considering that, under a monoculture, a 10% disease incidence is reached in most seasons, whereas in a crop rotation, it takes a number of seasons to reach the same level.

Slowing the epidemic rate with tolerant cultivars—Breeding programs to obtain tolerance are encouraged, but keep in mind that cultural practices should be the priority.

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Resumen

*La fusariosis de la espiga (*Gibberella zeae*; anamorfo:* Fusarium graminearum*) puede infectar al trigo en todas las zonas cálidas y húmedas donde se produce el cultivo. Las pérdidas de grano en la región de Planalto Médio de Rio Grande do Sul, Brasil, fueron en promedio de 103 kg/ha en un período de seis años. Se describe el ciclo biológico de este agente patógeno. Las principales fuentes de inóculo para la infección del trigo son los tallos viejos de gramíneas silvestres y malezas que el hongo coloniza como saprófito y que producen peritecios en abundancia. Esto asegura la presencia de inóculo en forma de ascosporas en el aire durante todo el año y, en especial, durante la floración del trigo. Los brotes de la enfermedad dependen en particular de las condiciones climáticas. No*

obstante, aún no se han determinado por completo los efectos de la duración de la humedad de la espiga y de la temperatura. Las principales medidas de control deben basarse en la tolerancia de la variedad (tasa de colonización del raquis) o su capacidad de escape (evitar que se infecten las anteras). Sería muy difícil lograr un control eficiente de esta enfermedad mediante la rotación de cultivos o el empleo de fungicidas.

El tizón foliar (causado por Bipolaris sorokiniana*) es una de las enfermedades más importantes en las zonas cálidas y húmedas donde se produce el trigo. El conocimiento de su ciclo biológico ayudará a formular recomendaciones para un control más eficiente. Las principales fuentes de inóculo son las semillas y los residuos infectados, el suelo que contiene conidios libres en estado de latencia y los huéspedes secundarios. Las medidas de control deben concentrarse en reducir el inóculo del hongo con los siguientes métodos: (1) distribuir a los agricultores sólo semillas con un bajo nivel de infección y tratadas con sustancias químicas eficaces, (2) combatir el agente patógeno en el rastrojo mediante la rotación de cultivos con especies no susceptibles durante por lo menos dos inviernos, (3) eliminar los huéspedes secundarios en la mayor medida posible y (4) mejorar para obtener tolerancia a la fase foliar de la enfermedad.*

Improved Scab Resistance in China: Sources of Resistance and Problems

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Abstract

Fusarium head blight (scab) caused by Fusarium graminearum *Schw.* (Gibberella zeae (Schw.) *Petch.) is one of the most important wheat diseases in China. Great progress has been achieved in breeding for resistance. After screening more than 30,000 wheat lines, the scab-resistance sources in Chinese wheat varieties were found to come primarily from moderately susceptible (MS) varieties. Pyramiding of scab resistance from Italian MS varieties and Chinese MS varieties has resulted in enhanced scab resistance in improved Chinese varieties. Since 1974, improved varieties with scab resistance, which were produced by making combinations among Funo and Mentana from Italy and Taiwanxiaomai from China, have become the main sources of scab resistance in improving Chinese wheat germplasm. New breakthroughs in scab resistance have not been achieved in the 1980s, probably due to the sources of resistance being limited to very few genotypes. To change this situation in the 1990s, new scab resistance sources must be found.*

Introduction

Fusarium head blight of wheat (scab), caused by *Fusarium graminearum* Schw. (*Gibberella zeae* (Schw.) Petch.), has been one of the most important diseases that hinders wheat production in China, especially in the middle and lower Yangtze River Valley, South China, and the eastern part of Northeastern China. Since the 1950s, high-yielding, but scab-susceptible varieties have been released and severe epidemics have occurred onthe average of once in 4 years in about 25% of China's wheat area, which encompasses some 17 provinces. It has been estimated that more than 5% of the total wheat production is lost in severe epidemic years. Therefore, studies on improving scab resistance in wheat have traditionally attracted attention.

Dai et al. (1941) first studied theproblem. Xia et al. (1955, 1956) studied scab resistance in detail by using artificial inoculation methods. Subsequently, the first generation of scab-resistantvarieties, such as Wannian 2, Emai 6, and Jinzhou 1, were released in China. By the 1970s, breeding for scab resistance had been quite successful and a number of varieties with different resistances were introduced in rapid succession (Jin et al. 1983, Zhou 1985). Sumai 3, bred by the Suzhou Institute of Agricultural Sciences in 1974, was the first scab-resistant variety derived from transgressive segregation. From 1974 to 1982, more than 30,000 wheat lines were screened in Shanghai and other provinces; from these morethan 1000 lines were identified as resistant (R) or moderately resistant (MR), among which were some excellent sources of scab resistance (All-China Cooperation of Research on Wheat Scab 1985, Liu et al. 1985). Since 1984, Wu and his colleagues have developed a gene pool with improved scab resistance by using the single dominant male-sterile gene Ta 1 and have tried to incorporate this resistance into high yielding genotypes through multiple-parent crossing and recurrent selection (Wu et al. 1984, Huang et al. 1989).

This paper discusses the scab resistance sources of improved varieties and problems in scab resistance improvement in China.

Breeding of Important Sources of Resistance and Resistant Varieties

Wannian 2 was the first moderately scab-resistant variety and was selected from Nanda 2419, a widely adapted variety that is moderately susceptible to scab. Wannian 2 was a good source of resistance and was used as the male parent crossed with the F_2 hybrid of two Italian varieties (Ardito and Tevere), resulting in Xiangmai 1 (MR-R), which also was a good source of resistance.

Intergeneric hybridization involving *Triticum aestivum* and *Secale cereale* (Nanda 2419/Jin Zhou rye) led to the development of a series of varieties with different resistances to scab, such as Jinzhou 1 (MR), Jinzhou 4 (MR), Jinzhou 10 (MR), and Jinzhou 47 (MS). Jinzhou 1, 4, and 10 have been used widely in the breeding program as sources of resistance. This is a successful example of scab resistance breeding that uses intergeneric hybridization between wheat and its relatives.

The well known variety Sumai 3, which came from the hybridization between two moderately susceptible varieties (Funo from Italy and Taiwan Xiaomai from China), was identified as a resistant variety. It attracted much breeder attention as a resistance source, resulting in its wide use in breeding programs for scab resistance. Using Sumai 3, the Jiangsu Academy of Agricultural Sciences has developed many resistant lines including Ning 7840 (R), Ning 7849 (MR), Ning 8017 (MR), and Ning 8026 (MR). The best of these—Ning 7840—was selected from the progenies of the hybridization between the F_2 of Abpopa/Anhui 11 and Sumai 3. After it was released, Ning 7840 soon became a source of resistance itself. Breeders are not only interested in its good scab resistance, but also its resistance to other important wheat diseases.

Sumai 8113, another excellent resistance source and variety bred from Sumai 3, has higher yield potential than Ning 7840 and can withstand scab infection in moderate epidemic years without fungicide application. Fujiang Agricultural College has developed six lines similar to Sumai 3 in scab resistance by crossing two MR varieties, Jinzhou 1 and Sumai 2. This was the first time that progeny with a high level of scab resistance were produced from two MR parents through transgressive segregation. Although these lines have some undesirable agronomic traits, they can be used as excellent scab resistance sources. Zhenmai 7495, which has been used as a resistance source, was also produced by pyramiding genetic resistance.

From the 1950s to the 1980s, almost all of the wheat growing areas in the middle and lower reaches of the Yangtze River were planted to varieties that were moderately susceptible to scab, but which had broad adaptation with high yield potential. In moderate epidemics, they showed some susceptibility, but still had a high grain yield. However, in serious epidemics, these varieties showed considerable susceptibility and without timely fungicide control, yields of these varieties would be significantly affected. Since the 1960s, selected lines of Funo, Yangmai 1, Yangmai 2, Yangmai 3, and Wumai 1 have been grown widely in the Lower Yangtze Valley region. Emai 6, which was developed by Hubei Academy of Agricultural Sciences through irradiation treatment, and Emai 9, a selected line of Emai 6, have been distributed over the Middle Yangtze Valley. Neixiang 5 was bred by crossing Nanda 2419 as the female parent with the mixed pollen of Baihuomai and Quality (USA) and Baimanmai (whose scab resistance can be traced to Nanda 2419). The scab resistance of Yaanzao (MS-MR) originated from a cross between three MS varieties. Yangmai 4 was bred from the cross, Nanda 2419/Triumph//Funo (Italian

varieties); both Nanda 2419 and Funo contributed to its scab resistance. Yangmai 5 and Een 1, which were bred in the 1980s, and grown in the lower and middle regions of the Yangtze River, respectively, have higher yield potential. The scab resistance of Yangmai 5 originated from the same sources as Yangmai 4; Een 1's resistance was derived from Sumai 3.

All these varieties have high yield potential, but do not have satisfactory scab resistance. On the other hand, many varieties with excellent scab resistance do not have desirable agronomic characters. This suggests that high resistance to scab does not combine well with high yield potential.

Scab Resistance Sources of Improved Chinese Varieties

Moderately susceptible varieties

Moderately susceptible varieties have played an important role in improving scab resistance. The scab resistance sources of 248 improved varieties with different resistances were analyzed. Table 1 shows that the scab resistance of 82.4% of the improved Chinese varieties originate directly from MS parents; the scab resistance of 4.8% of these improved varieties is derived from Sumai 3. Actually, the parents of Sumai 3 itself were MS varieties. Therefore, we can conclude that most improved varieties with different levels of scab resistance owe their resistance primarily to MS varieties. However, most crosses of MS varieties produced MS progeny and only a small number produced MR or R progeny through transgressive segregation.

Transgressive segregation - accidental or general occurrence?

Is transgressive segregation, the phenomenon by which scab resistance is pyramided, an accidental or a general occurrence? To find out, the pedigrees of R or MR materials screened from more than 30,000 wheat lines were analyzed. Of these materials, more than 50 varieties or lines were derived from transgressive segregation; 17 examples are listed in Table 2. Most of these materials are well known and their resistance to scab has been repeatedly identified. Table 2

Table 1. Scab resistance of parents of improved varieties with scab resistance.

Parents or treatment method	Resistance of parents	Resistance of bred varieties			Total	% of total
		R	MR	MS		
Nanda 2419	MS		5	35	40	16.1
Funo (Italy)	MS		7	41	48	19.4
Other Italian varieties	MS		1	19	20	8.1
Other foreign varieties	MS			21	21	8.5
Local varieties	MS[a]	1		18	19	7.7
Improved varieties	MS	7	6	7	20	8.1
Local var./ foreign var.	MS	1	2	24	27	10.9
Improved var./ foreign var.	MS		1	8	9	3.6
Sumai 3	R	2	7	3	12	4.8
Intergeneric crosses			4	13	17	6.8
Radiation treatment				15	15	6.0
Total		11	33	204	248	100.0
% of total		4.4	13.3	82.3	100.0	

[a] One of them was MR.

indicates that the scab resistance contained in S, MS, and MR varieties could be pyramided together when crossed in appropriate combinations. Transgressive segregation can occur when crossing varieties with varying degrees of scab resistance in appropriate combinations. It seems then, that transgressive segregation of scab resistance occurs often.

Could the type of cross that produced Sumai 3 be repeated to produce the scab resistance found in Sumai 3? It seems so since Huazhong Agricultural College obtained the line 7409, which was derived from the same cross that produced Sumai 3 and which has a resistance similar to Sumai 3. How did lines developed through transgressive segregation become the sources of scab resistance in the improved Chinese wheat varieties? Upon crossing, transgressive segregation apparently brought together genetic resistances dispersed in different varieties to form new varieties that had higher resistance and, certainly, could be new resistance sources to scab. Pyramiding of scab resistance relies on the fact that resistance to scab is polygenic (Nakagawa et al. 1955, Zhang and Pan 1982, Yu 1982, Chen 1983, Liao and Yu 1985).

The Italian wheats

About 43.6% of the improved Chinese varieties with scab resistance originated from Italian wheats. It seems that some of the Italian MS varieties have been the main sources of scab resistance. Italian wheats combined with local Chinese varieties produced many varieties with excellent scab resistance. Why did this happen?

Italian wheats, especially Nanda 2419 (Mentana) and Funo, had broad adaptation and other good agronomic characters and were widely grown in the Middle and Lower Yangtze River Valley during the 1950s and 1960s. Consequently, these varieties were used widely in local breeding programs,

Table 2. Examples of transgressive segregation of resistance to scab.

Parents and their resistance	Resulting varieties and their resistance
Funo(MS)/Taiwanxiaomai(MS)	Sumai 3 (R)
Funo(MS)/Taiwanxiaomai(MS)	7409 (MR-R)
Jinzhou(MR)/Sumai 2(MR)	Fan 50001, etc. (6 lines, R)
Sumai 2(MR)/Zhemai 1(MS)	Xiaofan 24 (MR-R)
Yecora F 70(S)/Fanshanxiaomai(MR)	Fan 635 (MR-R)
Rulofen(MS)/Fuzhoubaimai(MS)	Fumai 7 (MR)
Youyimai(S)/Emai 6(MS)	7406 (MR)
Xibei 612(S)/Funo(MS)	Jinguangmai (MR), Baijinguang (MR)
Zhongda 2509(MS)/Tevere(MS)//Wannian 2(MR)	Xiangmai 1 (MR-R)
Zhongda 2509(MS)/Anhui 10(S)//Tevere(MS)	Xiangmai 2 (MR)
Shangnong 205(MS)/Zhongda 2509(MS)//Neixiang 5(MS)	Xiang 868 (MR)
Nanda 2419(MS)/Lanxizhao(MS)	Jiulan (MR)
Fushuihuang(S)/Youyimai(MS)	Zhenmai 7495 (MR)
Yangmai 1(MS)/Aizhao(MS)	Jianyang 7705 (MR)
Yijiao 67-1-10(MS)/Dayeai(MS)	Jiumai 63 (MR)
Fuanbaihesh-ig(MS)/Yamatogmughi(MS, Japan)	Aiheshang (MR)
Funo selected line(MS)/Yimai 1(S)	Huazhong 2133 (MR)

ultimately resulting in a large number of varieties and selected lines being derived from these and other Italian materials.

Local Chinese varieties

In the regions of the Middle and Lower Yangtze Valley, there are a large number of local varieties—many of which have high and stable scab resistance. Up to now, however, only a small number of these MS varieties have been used in the breeding programs of these areas. Table 1 indicates that, if local MS varieties are combined with other varieties (especially foreign materials), the scab resistance of the hybrids could be increased.

The following are some local varieties that have been used successfully as sources of scab resistance:

- Taiwanxiaomai was combined with Funo (Italian), producing Sumai 3, an excellent resistance source.
- Linpuzao from Zhejiang Province was combined with Japanese and Italian wheats, producing Zhemai 1 and Zhemai 2.
- Ziangdongmen from Jiangsu Province was crossed with Rulofen (female parent), producing Early Nanda 1.
- Fuzhoubaimai (Fujian Province) crossed with Rulofen, resulting in Fumai 7.
- Mangou 335A-531 (MS-MR), which was a selected line from the local variety Daqingmang in Heilongjiang Province, was the scab resistance source for Heilongjiang Province varieties Hezuo 4 (MS), Kezhuang (MS), and Beixin 2 (MS).

Improved Chinese varieties resistant to scab

Most improved Chinese varieties with scab resistance originated from Italian wheats and local Chinese varieties. Since 1974, following the identification of their resistance to scab, these improved varieties have been the main sources of resistance. Using highly resistant varieties such as Sumai 3, Sumai 8113, and Ning 7840 has resulted in other highly resistant progeny; Sumai 8113 and Ning 7840 themselves were progeny of Sumai 3.

Although some of the first MR varieties—Xiangmai 1, Wannian 2, Zhenmai 7495, Aiheshang, etc.—are still being used as sources of resistance, breeders appear to be more interested in those MR lines derived from R and MR varieties, e.g., Ning 8017 and Ning 8026 bred from Sumai 3 and Ning 8343, Ning 8331, Fumai 5150, and Fumai 6101 bred from Ning 7840. These MR lines also have reasonable yield potentials.

Many MS varieties—Yangmai 1 through 5, Zhemai 1 and 2, and Emai 6—have been widely used in breeding for scab resistance due to their high yield potential and pyramided resistance to scab.

Other sources of scab resistance

A few varieties from other countries have also served as sources of scab resistance for some Chinese wheat varieties—e.g, Rulofen from Chile, Frontana from Brazil, Early Premium from the USA, and Yamatogmughi from Japan. All of these varieties are moderately susceptible and the varieties produced using these materials as resistance sources are moderately susceptible. It is worth noting that Early Premium bestowed MS on Beijing 8 (Bima 4/Early Premium); a number of varieties derived from Beijing 8 also acquired scab resistance.

Intergeneric hybridization between wheat and rye produced the MR varieties Jinzhou 1, 4, and 10. Recently, the intergeneric hybridization between common wheat and *Haynaldia villosa* produced R lines 87-88 P34 and 87-88 P35 (Liu and Chen 1983). It appears that

intergeneric hybridization between common wheat and its relatives can be an important new source of scab resistance.

Radiation treatment has not yet produced highly resistant varieties (Table 1). Most MS varieties treated with radiation remained moderately susceptible. However, radiation treatment has led to the development of a number of useful varieties such as Emai 6.

Problems in Scab Resistance Breeding

Selection of resistance sources

Unfortunately, seldom is there germplasm available that combines good agronomic characters with scab resistance. If a choice must be made, good agronomic characters are preferred, so during the 1950-1970 period all scab resistance sources used in breeding programs in China were MS varieties with good agronomic characters. Nearly all the sources were improved varieties. This led to the surprising situation that, although China has abundant scab-resistant germplasm, actual sources of resistance used have been confined to only a few varieties (as shown in Figure 1) where all the varieties used as sources are related to the varieties Funo, Mentana, and Taiwanxiaomai.

Table 3 shows the parents of the main scab resistance sources of 308 improved varieties identified as R or MR over the last 10 years. Obviously, breeding for scab resistance in China has over-relied on Funo, Nada 2419 (Mentana), and Taiwanxiaomai as the resistance sources.

Up to now, although no race differentiations have appeared in *Fusarium graminearum*, resulting in no loss of scab resistance, the scab resistance sources—especially Funo and its hybrid progenies—have lost some resistance to other diseases such as powdery mildew and leaf blight. This has complicated breeding for scab resistance. After analyzing the pedigrees of the varieties and advanced lines bred and identified during the 1980s, we can conclude that neither excellent resistance sources, such as Sumai 3, nor broadly adapted scab-resistant varieties, were produced during this decade.

Selection for scab resistance

It is important to have adequate disease pressure when selecting for scab resistance. The frequency of R and MR materials arising from the Middle and Lower Yangtze Valley has been much higher than that in north China or in other countries (Liu et al. 1985) because in these areas, scab epidemics occur frequently and there is a natural selection pressure. However, if selection is carried out only during natural epidemics, much time would be lost because severe natural epidemics occur, on average, only once every 4 years. For this reason, selection for resistance should be done from the F_1 to F_3 generations under artificially induced epidemics. In the F_1, the highly susceptible combinations should be eliminated; in the F_2, MS, MR, and R materials with good agronomic type should be selected; in the F_3, the head progeny row that escaped infection in the F_2 should be discarded. Using an MS variety as a check in the selection nursery is necessary to avoid discarding any excellent MS materials with high yield potential. A selection nursery should keep enough disease pressure so that highly susceptible materials are totally infected, while moderately susceptible materials have at least 50% infection of the spikelets.

Instability of field resistance to scab

Field resistance to scab in wheat varieties is restricted by interaction among the resistances of the varieties themselves, the causal organism (*F. graminearum*), and the environment. In wheat varieties, there are two types of resistance:

- The resistance to infection by the causal organism.
- The resistance to proliferation of the pathogen (Schroeder et al. 1963).

F. graminearum is a facultative parasite that can produce fusarium pathogenic toxin (Wang and Miller 1988, Xue et al., unpublished results). Fusarium toxin can cause electrolyte leakage (Yao et al., unpublished; Liu et al. 1989) and this

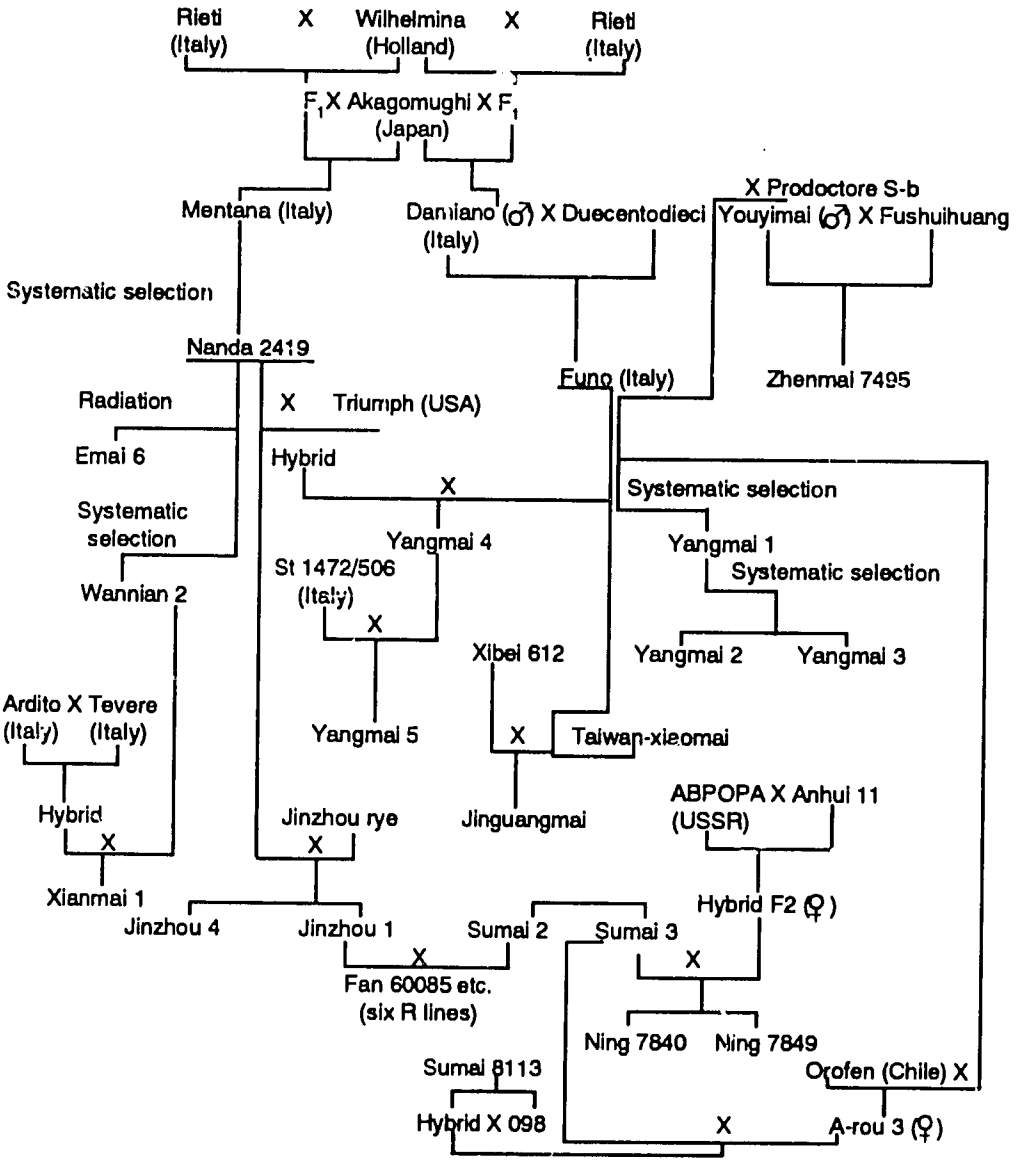

Figure 1. Pedigrees of main scab resistance sources in improved Chinese wheat varieties.

leakage provides substratum for the pathogen to develop. Provided the environment is suitable for the pathogen, the disease can develop. Both expression of resistance in wheat and pathogenicity of the pathogen are influenced by the climate. Climatic conditions will determine not only the disease's occurrence, but its severity as well. So, field resistance to scab shown by any wheat variety can not be stable and any method utilizing natural field testing, therefore, would not be stable either.

The following measures should make test results more reliable:

- Maintain a relatively stable testing environment. Of all environmental components, rainfall is the most important. Artificial rainfall facilities in scab nurseries are necessary to ensure consistent epidemic conditions.

- Use check varieties. Even if scab epidemics in the nursery are maintained at the appropriate levels, it is difficult to avoid varying disease pressures. For this reason, MS and R check varieties should be used as the "floating" comparison standards with which to compare varieties being tested every time.

Plant characters for selection toward resistance

While resistance to scab is complex, involving a genetic factor, physiological action, and some morphological and agronomic characters, a number of plant characters have been consistently correlated with the resistance.

Adaptation—Only when a genotype is well adapted to the growing environment will its resistance be expressed. For instance, Italian wheats were well adapted to the conditions of the Middle and Lower Yangtze Valley and their resistance, although only moderate, was easily identified. On the contrary, the CIMMYT wheats, which are poorly adapted to the region, cannot express any resistance that they may possess.

Grain-filling speed—It has been consistently observed that genotypes with a short grain-filling period often escape severe scab attack. The MR variety Zhenmai 7495 possessed this character.

Ripening stage resistance—Varieties with thin glumes or exposed grains usually have poor resistance to infection at the hard dough stage. Resistance in the ripening stage can be assessed after about 2 days of rainfall.

Table 3. Scab resistance data of main source parents of Chinese wheat varieties showing R-MR reactions.

Parent name	Resulting varieties			
	R	MR	Total	%
Funo	31	80	111	36.0
Nanda 2419 (Mentana)	5	45	50	16.2
Taiwanxiaomai		4	4	1.3
Funo-Nanda 2419	5	10	15	4.9
Funo-Taiwanxiaomai	55	56	111	36.1
Funo-Nanda 2419-Taiwanxiaomai	8	9	19	5.5
Total	104	204	308	
Percentage	33.8	66.2		

Ripening feature—It has been found that genotypes that have heads that stay green longest are more susceptible.

Head color—Varieties with deep green heads (and leaves) are usually more susceptible. Light green heads should be selected.

Use of fusarium toxin for screening cell clones

The fusarium toxin, deoxynivalenol (DON), can be detected in wheat heads 48 hours after inoculating with *F. graminearum*, indicating that it may be involved in pathogenicity at a very early stage of the disease.

DON has a greater influence on the activity of protoplasts from susceptible than from resistant wheat genotypes. This suggests that the toxin could be used to screen cell clones for resistance to scab. Research has shown that the appropriate concentration of DON for differentiation of resistance in wheat calli is about 10^{-2} to 10^{-3} mol/L. Lower concentrations (10^{-3} to 10^{-4} mol/L) are necessary for testing cell suspensions

While many resistant haploid and somatic cell clones have been identified in our program, it is not yet certain if this is the best method to enhance scab resistance. First, plantlets from calli of resistant varieties can have poor resistance in tissue culture—this has been the case with the R variety Wanshuibai. Second, plantlets from toxin-screened calli were not superior in scab resistance to those from calli that were not subjected to the toxin. Third, plantlets from calli treated with high concentrations of toxin were not necessarily resistant.

Classification of scab resistance

Up to now, scab resistance of wheat varieties has been classified as R, MR, MS, and S in China. With these classifications, there have been at least two problems. First, S varieties contain two large groups, one of which has all spikelets infected, the other in which not all spikelets are infected under severe epidemics. Second, highly resistant materials in related genera (Weng and Liu 1989) have not been categorized beyond R.

Obviously, a new classification system, where 0, HR, R, MR, MS, S, and HS delineations are used, would seem to be more reasonable. Materials with a 0 classification have not been recovered yet. Pedigree analyses of scab resistance sources for improved Chinese varieties have shown that transgressive segregation does not involve HS materials, indicating that these materials probably do not contain resistance genes for scab. However, some S grade materials were involved in transgressive segregation, showing that these materials might contain resistance genes for scab that could be pyramided (Table 2). Actually, some S materials were related to resistance sources, such as Yimai 1, Anhui 10, and Orofen (Chile), which are all related to Mentana. The suggested new classification would better reflect the genetic nature of scab resistance in wheat and would be useful in selecting parents for breeding work.

Development of new resistance sources

Utilization of relatively few resistance sources has limited further development of improved scab-resistant wheat varieties in China. Development of new resistance sources is a priority issue. The following activities would be useful in developing new sources:

- Identify widely adapted wheat germplasm that has absolutely no relationship to Funo, Mentana, and Taiwan-xiaomai.
- Transfer the genetic scab resistance from local Chinese varieties with excellent scab resistance to improved varieties.

- Further develop the gene pool with improved resistance to scab. If the gene pool is improved, the effect of pyramiding scab resistance would be better. MS and MR materials that have high yield potential could be used as the main parents. Resistance sources to scab need to be diversified. Genetic resistance of some excellent resistance sources, but without desirable agronomic characters, are better transferred into improved varieties before being used in the gene pool. HS materials should be excluded from the gene pool.

- Utilize the wild relatives of wheat. Weng and Liu (1989) have reported that *Roegneria ciliaris* and *R. kamoji* are highly resistant to scab. In 1989 these two species were identified and confirmed to be highly resistant in the Shanghai Scab Resistance Testing Nursery. This indicates that the relatives of wheat could be further utilized as gene sources for scab resistance.

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Resumen

El tizón de la espiga (roña) causado por Fusarium graminearum *Schw.* (Gibberrella zeae *Schw. Petch.) es una de las enfermedades del trigo más importantes en China. Se ha logrado un gran progreso en el mejoramiento para obtener la resistencia. Después de examinar más de 30,000 lineas de trigo, se encontró que las fuentes de resistencia a la roña en las variedades mejoradas de China provenían en esencia de variedades moderadamente susceptibles (MS). Desde 1974 se produjeron variedades mejoradas con resistencia a la roña combinando Funo y Mentana de Italia y Taiwanxiaomai de China. Estas líneas se han convertido en las principales fuentes de la resistencia a la roña en el germoplasma mejorado de trigo en China. No se han logrado nuevos avances en esa resistencia en el decenio de los 80, probablemente porque las fuentes de la resistencia están limitadas a muy pocos genotipos. Para cambiar esta situación en el decenio de los 90, es preciso encontrar nuevas fuentes de resistencia a la roña.*

Bacterial Diseases of Wheat in the Warmer Areas —Reality or Myth?

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Abstract
This paper presents the distribution of bacterial diseases affecting wheat and triticale and analyzes the variability among pathogens collected during 3 years from different traditional and nontraditional wheat growing locations. Xanthomonas campestris *pv.* undulosa, *the causal agent of bacterial leaf streak, is the major potential bacterial threat in warmer areas, but a new disease, bacterial sheath brown rot caused by* Pseudomonas fuscovaginae, *has been identified. Research of strategies to reduce bacterial streak incidence focuses on seed health, epidemiology, and production of resistant genotypes. Seed detection methods, including the use of dilution plating assay and monoclonal antibodies, are reviewed and the effectiveness of bacteriocide treatments is evaluated. The climatic factors involved in the transmission rate and symptoms expression are studied with the aim to clarify the disease cycle and to characterize disease-prone areas. Screening procedures for disease assessment are provided. This paper intends to analyze whether bacterial diseases of wheat are increasingly becoming a problem, particularly in the warmer areas, or are they mostly occurring in breeding programs where they have been ignored for years: are they a reality or a myth?*

Introduction

For years numerous reports of bacterial diseases have been made on cereal crops worldwide, but with the exception of bacterial leaf blight of rice caused by *Xanthomonas campestris* pv. *oryzae* (IRRI 1989), studies have been limited and quantitative information has been rare. This is notably true with wheat for which bacterial diseases are often considered unimportant. During the last decades, more outbreaks, sometimes caused by new pathogens, have been reported on wheat in very different geographical areas. This may be due to several factors:

- More research is being done on bacteria.
- Germplasm exchanges have increased and seed is often contaminated.
- Wheat is expanding into more disease-prone environments, i.e., the warmer and more humid areas.
- Mercury seed treatments are no longer utilized.
- Climatic changes appear in a limited region, but do not persist, thus favoring a "new" bacterial disease that may not remain a problem when those conditions no longer occur.

Bacterial Diseases of Wheat

Three major bacterial diseases are most importantly observed. *Pseudomonas syringae* pv. *syringae*, the causal agent of bacterial leaf blight (Shane and Baumer 1987), is probably widespread in nature and close to *P. syringae* pv. *atrofaciens*, responsible for basal glume rot (Wilkie 1973). Bacterial leaf streak (BLS) or leaf stripe, characterized by the production of yellow exudates under humid conditions and known as black chaff when found on the glumes (Smith et al. 1919), is caused by *Xanthomonas campestris*; it has a worldwide distribution (Duveiller 1989). Triticale seems to be particularly

susceptible (Cunfer and Scolari 1982). The other bacterial diseases (Bradbury 1986) usually have a more limited distribution or importance in some locations where the environment is more specific. Among the range of bacteria potentially able to infect wheat (Table 1), *X. campestris* pathovars only may cause significant losses in the warmer and humid areas. *Pseudomonas fuscovaginae*, causal agent of the bacterial sheath rot, recently identified for the first time on wheat (Duveiller and Maraite 1990), has only been reported in the Mexican highlands with an incidence less than 0.1%.

Differences among *Xanthomonas campestris* Strains

Since the first identification of BLS on wheat (Smith et al. 1919), several pathovar names have been used. The taxonomy of the *X. campestris* '*translucens* group' is particularly difficult (Schaad 1987a). The use by many authors of the name *translucens*, in a general sense when the host range was not defined, has led to confusion (Bradbury 1986). If the rules of the International Society of Plant Pathology are followed correctly (Dye et al. 1980), the pathovar

Table 1. Bacterial diseases naturally found on wheat, their symptoms, main areas of distribution, and some key references.

Bacterium and author citation[a]	Symptom	Distribution	Selected references[b]
Xanthomonas campestris pv. *undulosa* (Smith, Jones, and Reddy) Dye 1978	Leaf streak Leaf stripe Black chaff	Worldwide Brazil Mexico Pakistan USA China Zambia	 Mohan and Mehta (1985) Bamberg (1936) Akhtar and Aslam (1986) Smith et al. (1919) Sun Fuzai and He Liyuan (1986) Raemaekers (1988)
Pseudomonas syringae pv. *syringae* van Hall 1902	Leaf blight	Worldwide USA	 Shane and Baumer (1987)
Pseudomonas syringae pv. *atrofaciens* (McCulloch) Young, Dye and Wilkie 1978	Basal glume rot	Europa New Zealand Mexico, Syria	 Wilkie (1973)
Bacillus megaterium pv. *cerealis* Hosford 1982	Tan streaks and blotches	USA	Hosford (1982)
Clavibacter iranicus (Carlson and Vidaver) Davis, Gillapsie, Vidaver and Harris 1984	Gumming	Iran	Carlson and Vidaver (1982a)
Clavibacter michiganense subsp. *tessellarius* (Carlson and Vidaver) Davis, Gillapsie, Vidaver and Harris 1984	Mosaic	USA	Carlson and Vidaver (1982b)
Clavibacter tritici (Carlson and Vidaver) Davis, Gillapsie, Vidaver and Harris 1984	Tundu, Yellow ear rot	India, China, Ethiopia, Egypt	Gupta and Swarup (1972)
Erwinia rhapontici (Millard) Burkholder 1948	Pink seed	USA, Canada France, Israel	Roberts (1974)
Pseudomonas cichorii (Swingle) Stapp 1928	Stem melanosis	Canada	Piening and McPhaerson (1985)
Pseudomonas fuscovaginae Miyajima, Tanii and Akita *nom rev.* 1983	Brown sheath rot	Mexico	Duveiller and Maraite (1990)
Pseudomonas syringae pv. *japonica* (Mukoo) Dye et al. 1980	Black node, Blight, stripe	Japan	In: Bradbury (1986)

[a] The first three bacteria are causing the most important diseases of wheat.
[b] See Bradbury (1986) for more references and details.

name *translucens* should be reserved for strains specific to barley (Jones et al. 1917) and the name *undulosa* reserved for wheat and triticale strains. This issue may appear irrelevant for breeders who are interested in workable, fast screening methods, but consideration of pathogenic specialization is important when searching for BLS resistance. The latter seems to be partial and, consequently, is not easily observable under a strong inoculum pressure.

To analyze the differences among *Xanthomonas* strains from cereals, an International Bacterial Diseases Network (IBDN) was set up by CIMMYT and Unité de Phytopathologie, Université Catholique de Louvain, Louvain-la-Neuve, Belgium. It provides a wide range of strains isolated from cereal crops on a global basis. The recent study at Louvain-la-Neuve of pathotype strains corresponding to the original identification of *X. campestris* from cereals and gramineae showed that host range differences do exist and that precise identification of pathovars is justified. Plants of different crops grown up to the four-leaf stage were injected with sterile water until a drop was observed at the level of the upper leaf. A needle passed in a 24-hour bacteria culture on agar medium was used to prick the stem 5 cm above the soil level. After a 6-day incubation in a humid chamber, streaks were observed extending from the injury on the last leaf blade when host and bacteria were compatible (Table 2).

Leaves of the bread wheat genotypes, Alondra and Batuira, were infiltrated with a low concentration (10^4 CFU/ml) of *Xanthomonas campestris* pv. *undulosa* (Smith, Jones, and Reddy) Dye 1978 (*Xcu*) or *X.c.* pv. *hordei* (*Xch*) pathotypes. During the first days, *Xcu* multiplied at a rate similar to *Xch*, but the latter did not reach the threshold for induction of the leaf streak symptoms. In genotype Batuira, with some resistance to BLS, the differences were even clearer for the final population levels. Differences were less detectable with the susceptible genotype Alondra (Figure 1). Studies of bacterial multiplication in a set of wheat genotypes reveal differences in susceptibility as well as differences among bacterial pathotypes.

Table 2. Comparison of the host range of *Xanthomonas campestris* pathotype strains from cereal and gramineae, after inoculation by water injection and pricking wheat (Alondra), barley (Corona), and oat (Alfred) plants, at the four-leaf stage.

Strain[a]	Species	Origin	First Isolation of Plant Species	Host range		
				Wheat	Barley	Oats
NCPPB 2821	*X.c.* pv. *undulosa*	Canada	*Triticum turgidum* var. *durum* L.	+[b]	+	C
NCPPB 973	*X.c.* pv. *translucens*	USA	*Hordeum vulgare* L.	(+)	+	-
NCPPB 2820	*X.c.* pv. *hordei*	India	*Hordeum vulgare* L.	-	+	C
NCPPB 2822	*X.c.* pv. *secalis*	Canada	*Secale cereale* L.	+	+	C
NCPPB 1944	*X.c.* pv. *cerealis*	USA	*Bromus inermis* L.	+	+	C
NCPPB 1837	*X.c.* pv. *phleipratensis*	USA	*Phleum pratense* L.	-	-	C
NCPPB 2700	*X.c.* pv. *graminis*	Switzerland	*Dactylis glomerata* L.	-	-	C

[a] NCPPB = National Collection of Plant Pathogenic Bacteria, Harpenden, England.
[b] + = positive reaction, compatibility; (+) = weak positive reaction; - = negative reaction; C = chlorosis.

Most strains received in Belgium within the framework of the IBDN (Figure 2) corresponded to *Xcu* (Table 3). At CIMMYT Mexico, strains isolated from wheat, triticale, and rye were not crop-specific. Adding barley in inoculation tests, they were identified as *Xcu*, based on host range characteristics. In some years, the disease is naturally found on wheat and triticale plots, but not in barley, which suggests host specialization (Duveiller 1989).

In studies including bread wheat genotypes with different susceptibility to BLS, some *Xcu* strains from the warmer areas showed differences of aggressiveness or wheat genotype specialization (Table 4). Research on BLS in the greenhouse showed, however, that the host spectrum is not clear cut and unequivocal. Results suggest that resistance is not absolute and that genotypes may only be classified according to levels of susceptibility. In the field, differences among genotypes also seem quantitative and are characterized in the progress of infection from the lower part of the canopy toward the upper leaves, but the mechanism is not known. It is not yet possible to conclude whether races are existing in *Xcu*, like in *X.c.* pv. *oryzae* (Ou 1984) or in *X.c.* pv. *malvacearum* (Verma 1986), where pathogen variability is related to host genetics.

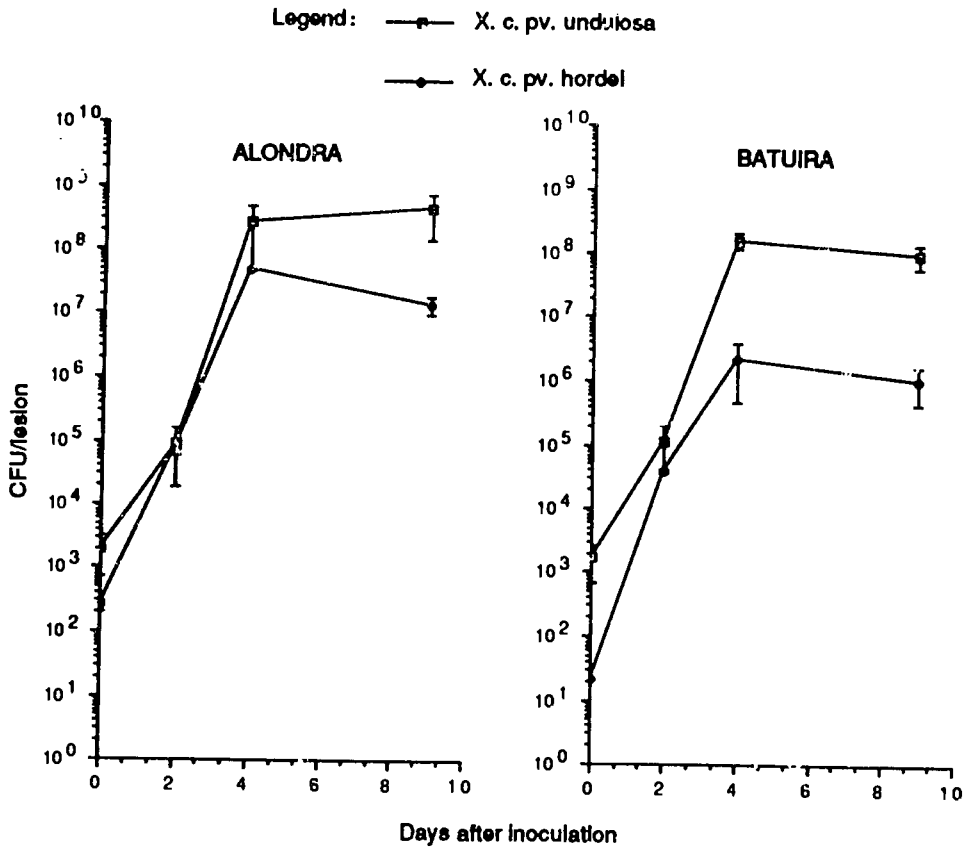

Figure 1. Multiplication of *Xanthomonas campestris* pv. *undulosa* (UPB 443 = NCPPB2821) and *X. campestris* pv. *hordei* (UPB 458 = NCPPB2820) in genotypes Alondra and Batuira in a 10^4 CFU/ml bacterial suspension.

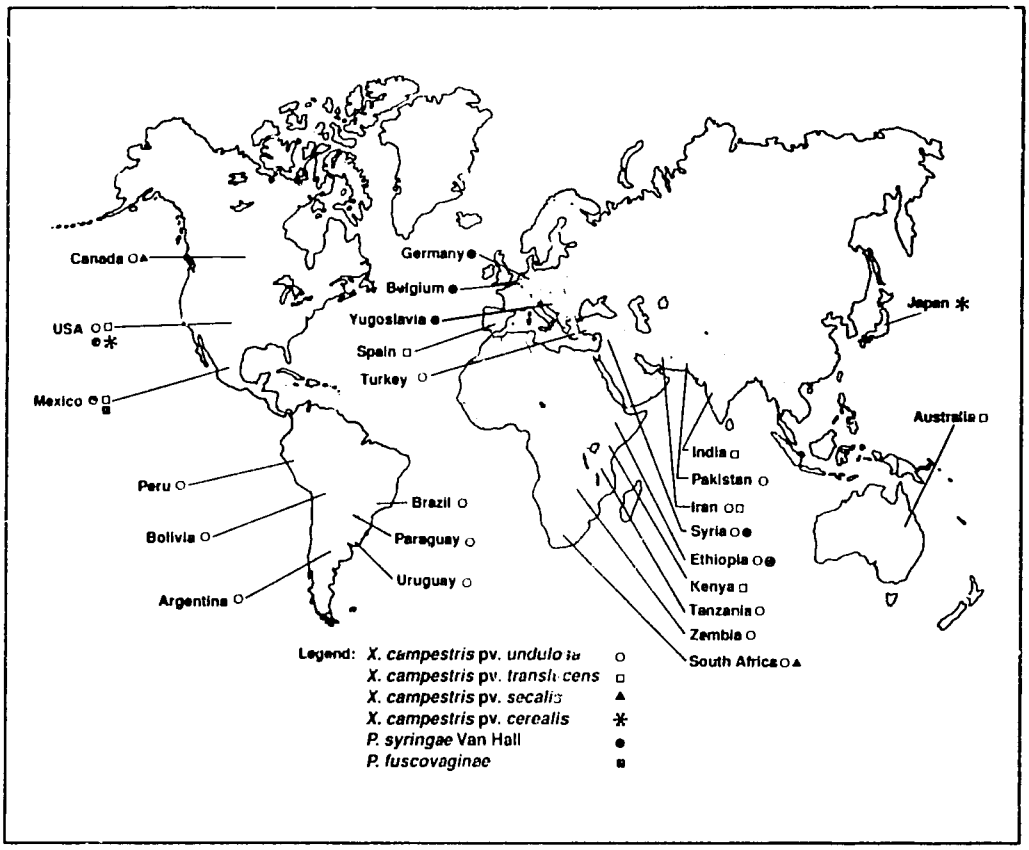

Figure 2. Distribution of bacteria obtained in Louvain-la-Neuve (Belgium) in the frame of the International Bacterial Diseases Network for wheat set up by CIMMYT.

Table 3. Host range of representative strains of *Xanthomonas campestris* pathovars (translucens group), obtained in the frame of the International Bacterial Diseases Network for wheat, after inoculation by water injection and pricking wheat (Alondra), barley (Corona), and oat (Alfred) plants at the four-leaf stage.

Strain[a]	Pathovar	Origin	Natural host	Host range		
				Wheat	Barley	Oats
UPB 480	*undulosa*	Pakistan	*Triticum turgidum* var. *durum* L.	+[b]	+	C
UPB 513	*undulosa*	Mexico	X *Triticosecale* W.	+	+	C
UPB 605	*undulosa*	Brazil	*Triticum aestivum* L.	+	+	C
UPB 645	*undulosa*	Syria	*Triticum turgidum* var. *durum* L.	+	+	C
UPB 676[c]	*secalis*	South Africa	*Secale cereale* L.	-	+	T
UPB 684	*translucens*	Iran	*Hordeum vulgare* L.	-	+	-
UPB 780	*translucens*	Spain	*Hordeum vulgare* L.	-	+	C

[a] UPB = Unité de Phytopathologie Bacterial collection, Louvain-la-Neuve, Belgium.
[b] + = positive reaction, compatibility; - = negative reaction; C = chlorosis; T = translucens spot.
[c] Received as pathovar translucens from J. Smith, Small Grains Centre, Bethlehem, South Africa.

Importance of BLS

Although BLS or black chaff has been reported frequently during the 1980s from areas as diverse as Argentina, China, USA, Mexico, Pakistan, Ethiopia, Turkey, and Brazil—which suggests that the disease is becoming important (Figure 2)—data on epidemiology are scarce. Some old reports were even possibly incorrect or unconfirmed. For example, black chaff was reported in Belgium by Marchal (1930), but the same author stated later (1948) that the disease was not found. Today BLS is considered not to occur in western Europe.

Most strains or samples received by the IBDN came from experiment stations and not from commercial fields. This may result from the more intensive observations of scientists who are familiar with bacterial problems at experiment stations. This probably led to the ambiguous statement that BLS is found mainly in breeding centers where the problem has been ignored for years (Schaad 1987b). In commercial fields particularly without sprinkler irrigation, exudates may not always be observed and identification without isolation of the pathogen may be difficult or dubious.

Yield losses are difficult to evaluate because no effective treatment and thus no healthy control plots are available. Shane et al. (1987) found that 50% disease severity on the flag leaf of spring wheat results in a 13-34% yield loss. A study over 2 years, using genotype Alondra in naturally infected plots in Mexico, showed that 23% yield losses can be expected when disease incidence is 100%, and 50% of the flag leaf area is damaged (Duveiller, unpublished). In triticale, losses up to 43% have been reported (Cunfer 1988); lines very susceptible to BLS, but promising for other characters, may not produce grain when infection is early and thus are eliminated from breeding programs.

Seed Detection and Seed Control

Survival of *Xcu* is poor in soils, but relatively better when crop debris is present (Boosalis 1952). The bacteria cannot survive more than 14 days in air dry soil and no more than 57 days when infected triticale leaves are mixed into moistened soil (Cunfer 1988). The major source of primary inoculum is the seed. Seed detection and treatment are the preferable ways to control BLS. Agar plating methods, combining seed wash, and the use of semi-selective media have been proposed (Schaad and Forster 1985, Duveiller 1989). They are reliable but testing many samples is time consuming; pathogens may be killed by antibiotics

Table 4. Average lesion extension (mm) and standard deviation observed on three bread wheat genotypes inoculated with three *X.c.* pv. *undulosa* strains from warmer areas.

Strain	Origin	Lesion extension[a]		
		Pavon	Tucano	Alondra
UPB 605	Brazil	4.4[b] ± 1.7	6.9 ± 2.6	11.0 ± 3.1
UPB 480	Pakistan	14.6 ± 4.0	17.5 ± 9.5	60.8 ± 19.7
UPB 513	Mexico	22.5 ± 9.49	2.0 ± 20.51	19.6 ± 41.1

[a] Inoculation by injection of sterile water and then pricking with a needle passed in a 24-hr old culture on agar medium.
[b] 10 replicates.

and thus underestimated; and the number of contaminated seed cannot be determined. Recently, monoclonal antibodies (Mas) specific for the *X. campestris 'translucens'* group, as determined after extensive testing with pathogenic and saprophytic bacteria from small grains of traditional and warmer areas, were developed by Bragard, Verhoyen, and Bazin (unpublished) at the Centre d'Application des Anticorps Monoclonaux, Unité de Phytopathologie, Louvain-la-Neuve. They were tested at CIMMYT on seedlots harvested in heavily infected plots, using Immunofluorescence microscopy (IMF) and Dot-ELISA techniques. In IMF, positive reaction was obtained using 40-μl drops of seed leachates (10 g seed/100 ml sterile saline) ranking from $5x10^4$ to $3x10^6$ colony forming units (CFU) per gram of seed, as determined with a plating assay on WBC agar. Using Dot-ELISA, the detection threshold seems to be 10^6-10^7 CFU/g seed. Both methods proved to be sensitive and specific. Complementary tests are currently in progress to better define the detection limits of both methods and a routine standardized serological test to discard heavily infected seed is expected for the near future.

Disinfection treatments have been studied and some of them, such as cupric acetate 0.5% at 45°C and dry heat (72°C) over 7 days were reported effective (Forster and Schaad 1989, Sands et al. 1989). However, poor correlation between field and laboratory tests using washing methods may occur (Duveiller, unpublished) due to either the heterogeneous distribution of bacteria and infected grains in the sample analyzed or due to a bacteriocide effect restricted to external bacteria. Moreover, a 95% reduction of pathogenic bacteria in the seed may not be sufficient to avoid an epidemic because of the extraordinary multiplication potential of bacteria when conditions are favorable. So far, no completely effective seed treatment is available, particularly on heavily infected seed (Table 5). The most promising

Table 5. Seed disinfection on heavily contaminated seed (harvest 1988, Toluca, Mexico) of genotype Alondra: comparison of infection level determined by seed washing at the laboratory and average percentage (three plots of 20 m²) of plants presenting symptoms in the field after booting stage (Toluca, 1989).

Seed Treatment	log CFU/g[e]	% Infected Plants	
		Toluca	Batan
Dry Heat 72°C, 7 days	BDT[b]	12.0 ab[c]	1.6 b
Rolitetracycline 1%, soaking 4 hr[a]	5.1	0.0 c[d]	4.3 ab
Cupric Acetate 0.5%, 40°C, 20 min[a]	5.0	7.3 abc	4.6 ab
Bordeaux Mixture (1 lb:1 lb:100 gal), 20 min, 40°C[a]	5.7	3.6 bc	6.7 ab
Formaline 0.8%, 1 hr[a]	BDT	9.4 abc	9.8 ab
Panoctine Plus, 400 ml/100 kg seed	5.2	12.5 ab	10.0 a
Cupric Acetate 0.5%, 45°C, 20 min[a]	BDT	14.2 ab	12.3 a
Kasugamycin, 2%, slurry	6.2	22.1 a	14.6 a
Copac E, 0.5 ml/50 g seed	6.1	11.7 ab	15.0 a
Control	6.5	17.0 ab	15.5 a

[a] Seed was rinsed after treatment.
[b] Below detection threshold (dilution 10^{-3}) on WBC agar.
[c] F test (arcsin): Toluca = 2.47 *; Batan = 2.48 *. LSD (P=0.05); treatments with the same letters are similar.
[d] Data possibly not reliable due to poor emergence.
[e] CFU = Colony Forming Unit.

control methods are not practical and may even be deleterious to the seed without the appropriate facilities. They should be combined with seed production in dry areas.

Disease Cycle and Effect of Environmental Conditions

Survival of *Xcu* in soil and plant debris is weak; it seems not to be a major cause of disease outbreak. Plant stubble usually decays very fast in the soil in warmer, humid areas and pathogenic bacteria cannot survive. At CIMMYT Mexico, wheat is grown in the highlands during the wet season and two growing cycles are separated by 6 to 7 months during which vetch is grown as the winter crop. *Xcu* is able to survive during that time on naturally infected straw kept under dry conditions in the laboratory. Wheat straw from the previous season is sometimes found at planting, but survival of *Xcu*, although theoretically possible, seems improbable due to rotation with a nonhost crop. Moreover, *Xcu* is very sensitive to antagonistic bacteria (Schaad and Forster 1985), including saprophytic fluorescent *Pseudomonas* (Duveiller, unpublished). The survival of *Xcu* on weeds and grasses is also possible due to the broad host range of the bacterium, but it is probably not significant in annual hosts. For example in Uruguay, severe streak symptoms caused by *Xcu*, as determined in host range inoculation tests, were found on canarygrass (*Phalaris canariensis* L.) used as border rows of experimental wheat plots in 1987.

In seed, the predicted extinction of the bacterium ranges between 63 and 81 months, according to storage conditions (Forster and Schaad 1989). Black chaff of wheat is considered to have a very low transmission rate. A low level of seed contamination will not result in field disease. In Idaho, more than 60% of all spring wheat seedlots have been found contaminated (Schaad 1987b). The multiplication capacity of the pathogen must, however, not be underestimated. In the wheat genotype Anahuac, the number of bacteria per lesion increases from about 10^4 to 10^8 in less than 48 hours. In inoculation trials with *X.c.* pv. *secalis* and *X.c.* pv. *hordei* on their respective hosts—rye and barley—the number of bacterial cells per cm^2 of infected leaf tissue increased from 10^4 to 10^8 in less than 24 hours (El-Banoby and Rudolph 1989). The high temperatures prevailing in warmer environments—*Xcu* grows ideally *in vitro* at 28-30°C—favor the growth of the organism. Indeed, *Xanthomonas* tolerates a rather wide range of temperatures (15-30°C) that can be found in many locations of the world, but where BLS is not necessarily observed. High humidity favors infection and the dissemination of the bacteria and thus the number of lesions. Bacteria enter through the stomata and multiply in large masses in the parenchyma causing elongated streaks limited by the veins that act as barriers. Milky or yellow exudates form on the surface of lesions. They are numerous in the morning when dew is maximum in the field, particularly on young lesions and at the adaxial side of leaf where the blade bends and where moisture remains longer. Like for *X.c.* pv. *oryzicola* (Ou 1984), these exudates become small yellow beads under dry conditions.

Rains and winds have a strong effect on the spread of these exudates and, consequently, on the spread of the disease from leaf to leaf throughout the field. But high rainfall during a short period, as frequently observed in the tropics, can also wash down the inoculum. Microinjuries caused by hail or wind through the contact of awns and leaves may possibly contribute to the penetration of bacteria into the blades. The role of aphids in long distance transmission seems possible, but only when host-tissue is water-congested (Boosalis 1952); this mechanism is probably limited.

Experimental evidence also indicates that root rot and leaf spot fungi, as *Pyrenophora teres* Drechs. and *Cochliobolus sativus* Ito and Kuribay predispose wheat to infection by *Xanthomonas* (Boosalis 1952). Although no extensive research has been done on that biotic relationship, it should be further investigated in warmer areas such as Brazil or Zambia (Raemaekers 1988) where both leaf blotch and BLS are found. This research may be difficult. In the warm area of Poza Rica, Mexico (49 masl), foliar damage caused by leaf blotch is usually so important that leaves are destroyed before BLS can be observed.

Since the bacterium has been found to be ice nucleating-active (Kim et al. 1987), frost effects on BLS epidemiology was investigated in an attempt to determine why the disease may be more severe (Waller 1976) in higher elevation areas. Azad and Schaad (1988) found that the susceptibility of wheat plants to *X.c.* pv. *translucens* increases considerably following frost and that BLS spreads more rapidly in frosted tissues. This mechanism, which may act sporadically including warmer environments, is not essential to induce an epidemic. In 1989, a dramatic epidemic was observed at El Batan, Mexico (2249 masl), starting at the end of July. The average maximum and minimum day/night temperatures during the 10 days preceding the first observations of symptoms were 25/7°C and were related to dew formation and tissue congestion (Duveiller, unpublished).

Thus, several necessary conditions have to occur successively to induce an epidemic (Figure 3). If one of the requirements for the disease cycle is not fulfilled at one moment, the epidemic can be stopped. This explains why BLS severity and distribution vary from year to year,

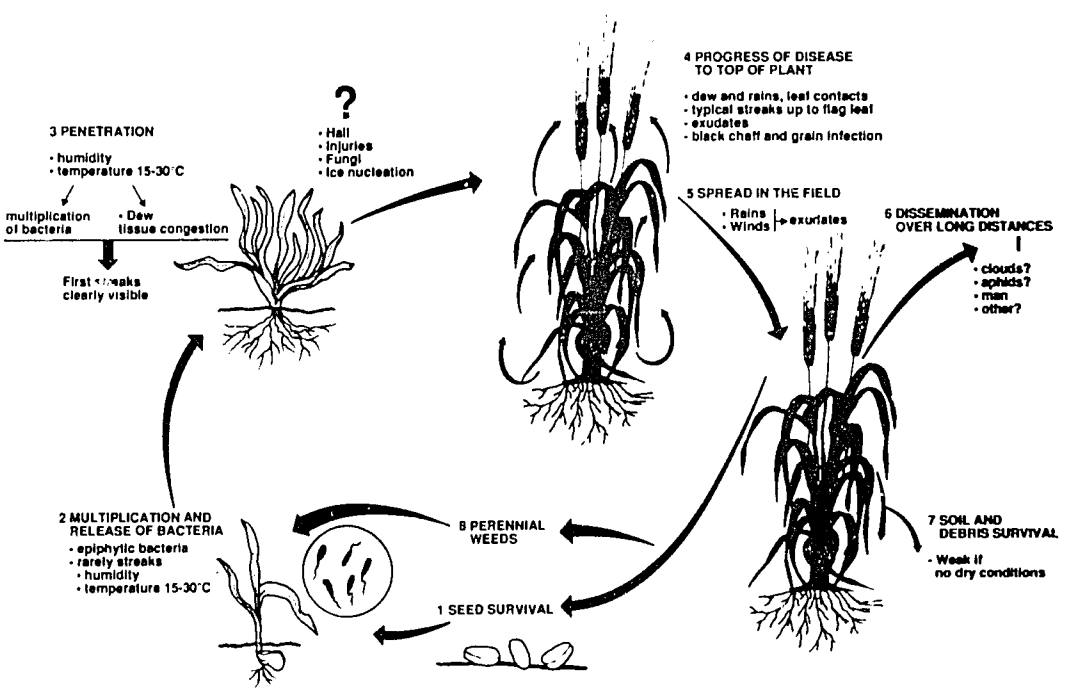

Figure 3. Life cycle of bacterial leaf streak or black chaff caused by *Xanthomonas campestris* pv. *undulosa*.

including in disease-prone areas. Mexico's Toluca Valley is considered an ideal location to study BLS on wheat and triticale. This was confirmed in 1988, but not in 1989 (Table 6). In the same disease-prone location, during the same season, two inoculations done at different times may also prove to be dissimilarly effective if climatic conditions vary. This makes the research on epidemiology and resistance to BLS particularly difficult. It demonstrates why the disease has a global distribution and is rather sporadic in areas as different as sprinkler-irrigated wheat fields in the USA, Mexican highlands characterized with marked diurnal temperature changes, and countries of the Southern Cone of South America where warm and cloudy days may occur alternately. Thus, bacterial diseases of wheat are a reality, but with a variable risk of occurrence. They may appear unimportant for years, but suddenly become very devastating if the combination of factors inducing the epidemic is encountered. Because of their temperature and humidity characteristics, warmer, nontraditional wheat growing areas will remain more subject to that risk.

Table 6. Bacterial streak severity (Saari-Prescott two-digit scale) in two Mexican locations and four triticale genotypes scored at 10.5 stage, in 1988 and 1989.

Genotype	1988 Toluca Aug. 23	1988 El Batan Aug. 24	1989 Toluca Aug. 24	1989 El Batan Aug. 23
Venus	7.4	6.3	3.1	6.2
Siskiyou	8.3	5.2	2.1	7.2
Buffalo	7.3	5.4	4.1	7.3
Stier	9.4	9.4	6.2	7.3

Breeding for Resistance

Since disease control by seed treatment is not satisfactory, development of resistant genotypes appears to be the best way to limit the risk of yield losses due to BLS. It is essential that the material to be screened is exposed uniformly to the pathogen. This is possible only through artificial inoculation. Because of the sporadic character of the epidemics, natural infection is too unreliable and heterogeneous in the field to be useful for efficient screening. At CIMMYT, inoculation in the field is accomplished by spraying a concentrated bacterial suspension in the afternoon when plants are at the tillering stage. Disease rating is done at flowering, using the scale proposed by Saari and Prescott (1975) for appraising the foliar intensity of wheat diseases. The disease progresses according to a vertical gradient as shown by damaged leaf area lower for flag leaf than for the flag-one leaf. Black chaff and stem melanosis are not typical of *Xcu*. Due to abiotic melanism in wheat induced by high temperature and humidity (Johnson and Hagborg 1944), considering the ear when using the scale is not recommended, particularly in genotypes containing the *Sr2* resistance gene for stem rust. Stem melanosis may also be induced by *P. cichorii* (Piening et al. 1989), a bacterium that is found in warmer areas.

When greater details are required, the scale may be modified by the use of a second digit corresponding to damaged leaf area. For BLS, only one scale was proposed to score severity of leaf damage (James 1971); however, it is not representative of all the symptom patterns found in the field.

Although some genotypes are well known for their resistance or susceptibility to BLS, little is known on the genetics of resistance to the disease. In wheat, Woo

and Smith (1962) showed that resistance to the bacterium was controlled by a single genetic factor pair, BcBc. More recently, a study conducted on three triticale lines indicated the presence of a single dominant gene in each of three lines resistant to BLS: Siskiyou, M2A-Beagle, and OK 77842. These three genes are either the same or closely linked (Johnson et al. 1987).

In other field studies on six triticale genotypes under inoculum pressure, the disease progress curves appeared to be different (Figure 4). Some entries were characterized by a slower disease development, but more research is required to understand the components of this slower disease evolution.

Conclusions

Bacterial diseases of wheat and triticale are a reality, but a combination of favorable environmental factors is necessary to guarantee an epidemic. Warmer, nontraditional wheat growing areas have all the characteristics required for BLS outbreaks and, therefore, can be considered as potential hot spot areas. The disease will not appear every year and severe losses are unpredictable. This makes study of the disease quite complicated. Research is nevertheless desirable to better understand the epidemiology and obtain effective resistance. The latter is the most secure way to limit the risk of disease since BLS cannot be controlled effectively with bacteriocide treatments.

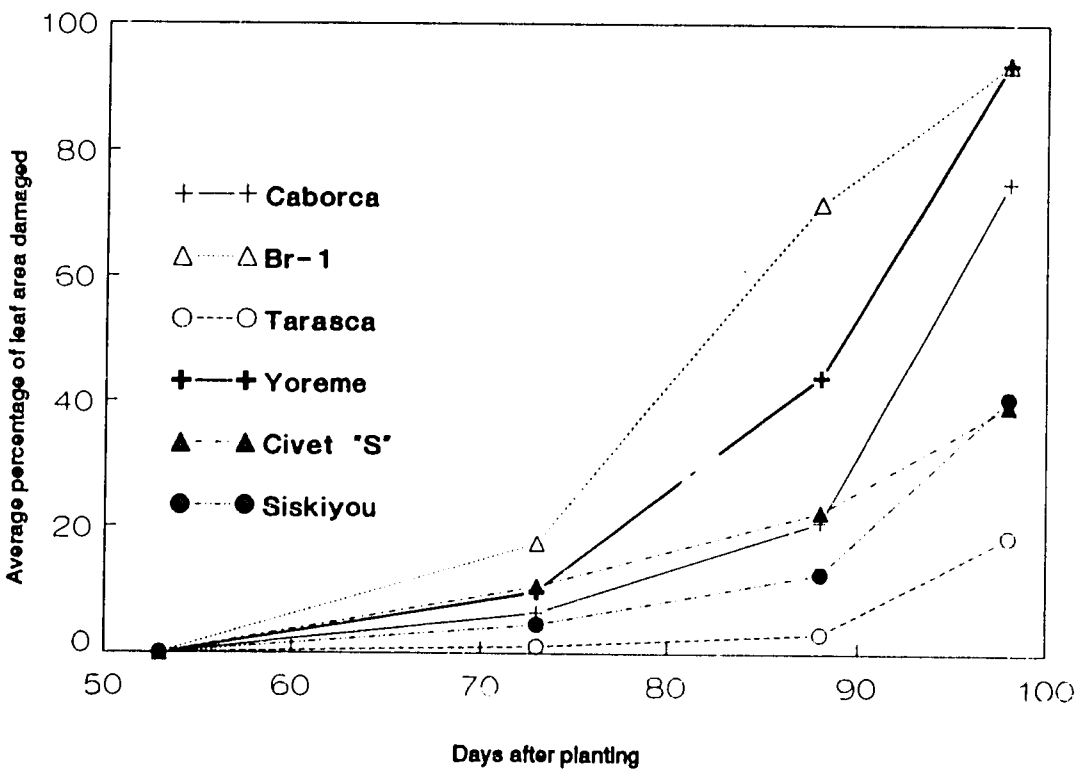

Figure 4. BLS disease progress curve in triticale.

Acknowledgments

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Resumen

En este trabajo se presenta la distribución de las enfermedades bacterianas que afectan el trigo y se analiza la variabilidad entre los agentes patógenos reunidos durante tres años en distintas localidades, donde es tradicional o no tradicional el cultivo del trigo. Xanthomonas campestris *pv.* undulosa, *el agente causal del rayado foliar bacteriano, es la principal amenaza bacteriana en las zonas cálidas, aunque se ha identificado una nueva enfermedad, la pudrición bacteriana café de la vaina, provocada por* Pseudomonas fuscovaginae. *La investigación de estrategias para reducir la incidencia del rayado bacteriano se concentra en la sanidad de la semilla, la epidemiología y la producción de genotipos resistentes. Se examinan métodos para la detección en la semilla, incluido el empleo del ensayo de dilución en placas y los anticuerpos monoclonales, y se evalúa la eficacia de los tratamientos bactericidas. Se estudian los factores climáticos que influyen en la tasa de transmisión y la expresión de los síntomas, con el propósito de esclarecer el ciclo de la enfermedad y caracterizar las zonas propensas a ésta. Se señalan procedimientos de examen para evaluar la enfermedad. Este trabajo pretende determinar si las enfermedades bacterianas del trigo constituyen un problema cada vez mayor, en particular en las zonas cálidas, o si se presentan principalmente en los programas de fitomejoramiento que durante años no las han tomado en consideración. ¿Son un mito o una realidad?*

Development of Aphid-Resistant Wheat Germplasm

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Abstract

Aphids are among the most destructive insect pests of wheat throughout the world. Current methods for controlling these pests rely heavily on insecticides, high cost inputs that must also be considered as environmental hazards. The use of insect-resistant cultivars is one of the most desirable alternatives to insecticides and is a key component in an integrated pest management system. By enhancing the plant's innate ability to tolerate insect infestations and using the improved cultivar in combination with novel cropping practices, we have been able to reduce resulting damage and decrease pesticide use. However, developing and releasing resistant wheat cultivars remains an ongoing concern as new aphid pests appear and as new aphid biotypes that overcome resistance are detected. This paper discusses approaches and concerns involved in breeding wheats for resistance to aphids.

Wheat, *Triticum aestivum* L., is attacked by several different aphid species worldwide. The most economically important species include the greenbug, *Schizaphis graminum* (Rondani); the Russian wheat aphid, *Diuraphis noxia* (Mordvilko); the bird cherry-oat aphid, *Rhopalosiphum padi* (L.); the English grain aphid *Macrosiphum avenae* (F.); and the corn leaf aphid, *Rhopalosiphum maidis* (Fitch). Feeding damage by these aphid pests is sometimes severe and can reduce both yield and grain quality. Little is known about the physiological, molecular, and biochemical nature of aphid feeding damage to cereals. However, feeding injury to intact wheat plants has been characterized by Ortman and Painter (1960), Kieckhefer and Kantack (1980), Pike and Shaffner (1985), and Burton (1986). Al-Mousawi et al. (1983) published photomicrographs showing detailed ultrastructural greenbug feeding damage in wheat. In addition to direct feeding damage, many of the wheat aphids serve as vectors of serious virus diseases, such as barley yellow dwarf (BYD), which further amplifies their importance as pests.

In the United States, considerable research has focused on the development of plant resistance to greenbugs and Russian wheat aphids and, to a lesser extent, on other aphid species. In the case of greenbug, the process of developing and deploying resistance in wheat has become complicated by the advent of virulent biotypes that could rapidly overcome the resistance sources as they were deployed in the field. Hatchett et al. (1987) recently reviewed the history of resistance to greenbugs in wheat. Wood (1961) reported the first greenbug biotype, B, followed by biotype C (Harvey and Hackerott 1969), biotype E (Porter et al. 1982), biotype F (Kindler and Spomer 1986), and biotypes G and H (Puterka et al. 1988). This history of greenbug biotypes is outlined by Puterka and Peters (1990). Dahms et al. (1955) found the first source of resistance for greenbug in wheat in 'Dickinson Sel. 28A'.

In 1974, Wood et al. (1974) identified resistance to biotype C in the triticale 'Gaucho'. Resistance in Gaucho is conditioned by a single dominant gene derived from 'Insave F.A.' rye (*Secale cereale* L.) (Arriaga 1956). Sebesta and Wood (1978) transferred the resistance

from Gaucho, resulting in the hexaploid wheat line 'Amigo'. The single dominant gene for biotype C resistance was located on chromosome 1A (Hollenhorst and Joppa 1983). The Amigo germplasm has been used extensively in breeding programs worldwide, and several cultivars with Amigo resistance have been released in the United States. Amigo also has resistance to powdery mildew and wheat streak mosaic virus. Unfortunately, the Amigo resistance for biotype C was overcome by biotype E which was detected in 1982 (Porter et al. 1982). Consequently, cultivars with resistance to biotype E, the predominant biotype in the field (Kindler et al. 1984), are currently needed.

Resistance to biotype E has been characterized in *Triticum tauschii* (Coss.) Schmal. as a single dominant gene and has been incorporated into the germplasm 'Largo' (Joppa and Williams 1982), in *T. tauschii* var. *stranqulata* (Harvey et al. 1980), in *Triticum speltoides* (Tyler et al. 1985), and in triticale (Webster and Inayatullah 1984). Tyler et al. (1987) found five different genes for greenbug resistance and designated them as Gb1 through Gb5. A better understanding of the biology and genetics of greenbug biotypes (Puterka 1989) combined with the early field detection of new biotypes and improved plant breeding techniques should increase the successful development and deployment of wheats with resistance to greenbugs. Wheat germplasm with vertical resistance to several greenbug biotypes has been developed and released in the United States.

The detection of the Russian wheat aphid (RWA) in South Africa in 1978, Mexico in 1980, and the United States in 1986 (Stoetzel 1987) has caused a shift of emphasis in wheat resistance programs. The importance of this pest to the U.S. wheat industry is substantiated by the reported economic damage in 1988 of over US$130 million (Peairs et al. 1989). Plant resistance studies were initiated in the United States soon after the RWA was detected (Webster et al. 1987a,b). Concomitant with the arrival of the RWA in the United States, Du Toit (1987, 1988) in South Africa reported resistance in wheat to RWA. Subsequently, additional RWA resistance in wheat and other cereals has been reported (Quick et al. 1989; Meyer et al. 1989; Bush et al. 1989; Webster 1990; Webster et al. 1990a,b; Du Toit 1989a,b). These sources of resistance are currently being utilized in breeding programs to improve wheat and barley germplasm.

Techniques for Locating Aphid Resistance in Wheat

Sources of resistance

Evaluating germplasm collections is a common method of searching for aphid resistance. Collections are maintained by international, national, state, and local authorities in many countries. In the United States, the U.S. Department of Agriculture maintains an extensive wheat collection (more than 43,000 lines) at Aberdeen, Idaho. Various international agricultural institutions, like CIMMYT in Mexico, the FAO in Rome, and the N.I. Vavilov Institute in Moscow, also maintain significant collections. Smith (1989) lists additional world collections of wheat germplasm. State and private breeders usually maintain smaller "working" collections. These collections also supply wheat workers with the germplasm needed in host plant resistance breeding programs.

A promising approach for finding resistant plants within large collections is to request lines originally collected where the insect is indigenous or from the center of origin of the host species. In the case of the RWA, plants from the geographic

endemic population center of the RWA were initially selected; this approach was successful in that several sources of resistance for several small grains were located (Webster et al. 1990a,b).

When selecting lines for resistance evaluation, adapted cultivars and advanced lines are more desirable because they generally have greater crossability and better agronomic characteristics, thus requiring less time in a breeding program. Certainly, good resistance genes occur in related wild species and should be noted for future use or carried along in the program for use, if and when they are needed. For example, Baker et al. (1989) first found resistance for RWA in *T. tauschii*, but program emphasis was changed when resistance was found in hexaploid lines (Webster et al. 1990b).

Insect rearing

Large numbers of aphids are required for mass screening. Generally, rearing large numbers of aphids on plants is quite simple if adequate glasshouse space is available. The technique described by Starks and Burton (1977) has been very successful and is still used today for both the greenbug and the RWA. In general, the technique uses a susceptible host plant; barley is a preferred host for both greenbug and RWA and can be expected to give the best population growth. Plants are grown in 20-cm pots in soil, a soil-sand-peat mix, or fritted clay (Burton 1986). The pots are caged with cylindrical plastic cages (about 35 cm tall) that are vented on the top and sides; cages exclude extraneous insects and confine the aphids. Optimal temperature is dictated by the requirements of both the barley plants and the aphids; neither do well under heat stress. In warmer regions, greenhouse screening of test plants for resistance may need to be restricted to the cooler months. Artificial lighting for extending the photophase to 16-18 hours is required in temperate latitudes to prevent holocyclic species from going into a sexual cycle, and thus reducing progeny output. Most aphids will continue parthenogenetic reproduction indefinitely when photophase and temperature are controlled (Blackman 1988). Auclair (1989) recommends the use of homogeneous populations to determine the genetics and nature of resistance in plants. Individual progeny of clones or specific biotypes, as described by Blackman (1988) and Puterka (1989), are recommended for more basic studies.

Problems encountered during rearing can be the invasion of aphid parasites, plant mildews, and contaminants from other aphid cultures. Clean, dry working conditions, combined with good sanitation and, if possible, isolation of test colonies in separate greenhouses are essential in preventing these problems. Watering plants too frequently can promote mildews and other plant diseases.

Planting and infestation

Aphid infestations of seedling populations are relatively easy to manage in the greenhouse in a plant resistance breeding program. Ten rows are marked with a soil row marker and planted with 30 seeds of each entry to be tested. This method identifies low levels of resistance and segregation; however, when a very large number of lines are to be screened, a modification of this technique can be used. Entries are planted in 60 "hills" per flat (51 x 35 x 9 cm) with five seeds per hill instead of the 10 rows per flat. To facilitate planting, a soil marker that makes 60 depressions (1.8 cm deep) in the standard greenhouse soil mixture is used, resulting in a hill-to-hill distance of 4.5 cm. This procedure, although not as sensitive, allows a greater number of entries to be tested in each flat compared with the usual row method (Webster et al. 1990a).

When single-leaf seedlings are about 6 to 7 cm high (3 days after plant emergence), they are infested with a mixture of approximately 10 nymphs and apterous adults per plant by placing infested detached leaves from the culture pot on the soil between test plants.

Evaluation of entries

It is important to have at least one row or hill planted with a susceptible entry as a check in order to precisely follow progress of the test. If available, the inclusion of a resistant entry is also valuable for comparative evaluation. Damage ratings are generally used to visually evaluate entries. Starks and Burton (1977) describe this procedure. For greenbug damage, a standard 1-to-9 rating system, where 1 = no damage and 9 = dead plant, is typically used (Starks et al. 1983). Intermediate damage ratings are based upon incremental levels of chlorosis and necrosis. However, this system has not been effective for RWA because the expression of plant damage caused by the RWA is substantially different from that caused by the greenbug. The rating system developed to characterize RWA feeding damage on seedlings (Webster et al. 1990b) is based on two components of damage exhibited by the plant: percent chlorosis (chlorotic spots or streaking) and leaf rolling. Percent chlorosis is based on a 1-to-9 scale , where:

- 1 = plants appear healthy, may have small isolated chlorotic spots.
- 2 = chlorotic spots become more noticeable, up to 5% of total area.
- 3 = chlorotic spots are larger and more numerous, up to 15% of total area.
- 4 = chlorosis covers up to 25% of total area, some streaking may become apparent, especially along midrib.
- 5 = chlorotic spots begin to coalesce or definite streaking may occur, chlorosis covers up to 40% of leaf area.
- 6 = larger chlorotic areas from coalesced spots, leaves starting to "die-back" from tips, chlorosis covers up to 55% of leaf area.
- 7 = further symptom development, chlorosis covers up to 70% of leaf area.
- 8 = extensive chlorosis and necrosis, up to 85% of leaf area affected.
- 9 = plant death or plant damaged beyond possible recovery.

The second component of damage (leaf rolling) is characterized as either F (leaves are flat, with no apparent rolling), or R (leaves are loosely to tightly rolled). Characterization of resistance levels by damage rating score is:

- Resistant (1F to 3F).
- Moderately resistant to moderately susceptible (4F to 6F).
- Susceptible (7F/R to 9F/R).

Further testing or retesting of lines found to be resistant is always in order. If testing in hills, moving to the single rows and replicating may be a good secondary procedure to verify resistance and determine if entries are homogeneous for resistance.

If the resistance components of antibiosis, antixenosis, and tolerance are to be determined, the techniques utilized by Webster et al. (1990a) for greenbug and RWA are good standards. Tremblay et al. (1989) used somewhat different techniques for the bird cherry-oat aphid. Understanding the components of resistance is desirable when selecting

between resistant entries for the breeding program. Tolerance is preferred because it is less likely to introduce selective pressure on the aphid population, which may enhance the development of new biotypes.

Evaluating plant entries for intermediate RWA resistance is difficult because damage may not be visually apparent in the screening test (Burd et al. 1989). The effect of aphid feeding can be best determined by comparing specific growth characteristics of aphid-damaged plants with an untreated control. Plant components that can be quantitatively measured are tiller and leaf development, total leaf area, and total leaf length. Burd et al. (1989) reported that analysis of plant growth components revealed substantial differences between RWA-infested and control plants and stated that traditional damage rating schemes were adequate for identifying susceptible entries but performed poorly in measuring intermediate damage levels. In their studies on RWA damage, plant stunting best predicted the quantitative damage responses.

Development of Resistant Germplasm

Saving resistant plants

It is important to recover resistant plants from the screening tests for several reasons. Generally, seed supplies for screening are extremely limited and not always of good quality. Some sources of seed may be contaminated with mixed seed, and some sources may be nonhomogeneous for resistance. Plants from the screening tests that proved resistant can provide a new, fresh source of seed. Cereal plants generally transplant well and can be moved to larger containers where they can mature. Progeny should be tested to confirm the resistance.

Breeding scheme(s) utilized in breeding for aphid resistance

The breeding scheme used to develop aphid-resistant wheat germplasm depends on the type of inheritance of the resistance response detected. In general, plant resistance to aphids is conditioned by single genes. The identification and characterization of single, dominant genes (Gb1 through GB5) conferring resistance to virulent greenbug biotypes formed the basis for a model system of insect-plant interactions and wheat germplasm enhancement. The introgression of these single gene traits into wheat germplasm using the traditional approach of backcross breeding has proved very effective in developing greenbug-resistant cultivars.

Preliminary work on the genetic control of two sources of resistance to the Russian wheat aphid suggests that each source of resistance is conditioned by separate single, dominant genes (Du Toit 1989b). Given the single gene nature of this resistance, development of Russian wheat aphid resistant cultivars would be effectively facilitated by the backcross breeding method.

Selection of an appropriate background

Ideally, when a new aphid pest is introduced (e.g., the Russian wheat aphid), the wheat breeder would have access to adapted resistant germplasm with varying agronomic traits that could easily be used in a breeding program and would require minimal backcrossing to elite germplasm before release. However, resistance genes generally have been detected only in unadapted landraces, or in related species; in some cases, the resistance genes are tightly linked with undesirable traits. This linkage needs to be broken before introgressing the resistance genes into elite germplasm.

Given the large scope and limited resources of the typical breeding program, breeders usually cannot afford to maintain the type of germplasm program needed to move resistance genes from unadapted germplasm or related species into the breeding program. In this situation, programs designed specifically to develop aphid-resistant germplasm would select a series of adapted germplasm with varying agronomic traits and growth characteristics (e.g., hard red winter, soft white spring) and incorporate resistance genes. Consequently, these materials would be developed to the point where they could be readily utilized in a diverse array of breeding programs throughout the world.

Genetic control and tracking the resistance during breeding

Following the identification of a resistance source, the genetic control should be determined through conventional methods (e.g., analysis of segregating F_2 populations of resistant/susceptible hybrids). Once the number of genes involved and their inheritance patterns has been determined, tracking the resistance genes in the breeding program is simply a matter of testing levels of resistance of progeny through seedling evaluation of damage from aphid feeding, as outlined under evaluation techniques. In the example of the single, dominant gene being transferred by the backcross breeding method, the backcross progeny would be tested at the seedling stage, and resistant selections saved for crossing to the recurrent parent.

The testing of backcross progeny and tracking of resistance genes using aphid/plant damage evaluations is costly in terms of resources and time. In addition, valuable resistant germplasm can be lost if testing conditions are too severe. Often the stress of transplanting or vernalizing seedlings that have been tested for aphid resistance is too much, resulting in seedling mortality. Due to these concerns, the development of marker-facilitated screening assays should be a high priority research objective. The identification and characterization of molecular or cellular markers associated with resistance genes would greatly enhance the development of aphid-resistant germplasm.

Interspecific hybridization program

Because of the introduction of new aphid pests (e.g., the Russian wheat aphid) and the biotypic variation existing within aphid populations (e.g., greenbug), new sources of resistance must be identified and deployed. The logical sequence in the search for resistance sources would be to test all available accessions within the species beginning with adapted germplasm, followed by unadapted accessions. If no resistance is found, or if levels of resistance are inadequate within a species, the search must move outside the species. The identification and transfer of genes that confer resistance through interspecific hybridization programs have proved invaluable in aphid resistance breeding. Several interspecific hybridization programs around the world are currently moving genes across species barriers.

Certain obstacles must be overcome in order to move resistance genes from one species to another. In general, there are incompatibility problems that affect both development of viable embryos and limit genetic recombination. Fortunately, tissue culture techniques have been developed that allow the rescue and *in vitro* culture of immature embryos, resulting in viable plantlets. Chromosome doubling with colchicine, X-ray irradiation treatment, and *in vitro* callus culture has aided in transferring resistance. These techniques are designed to overcome barriers that have evolved during speciation. As such, they require more work and patience than intraspecific hybridizations, but the

rewards in terms of utilizing unique resistance sources and expanding genetic diversity are well worth the effort.

Future of plant resistance to aphids in wheat

The recurring theme driving breeding for aphid resistance has been the shift of biotypes within aphid populations toward virulent biotypes that overcome resistance genes deployed in wheat. The resulting mode of operation has been to deploy resistance genes, wait for the aphid population to shift, identify new aphid biotypes, identify and deploy resistance genes against the new biotype, and perhaps begin the cycle anew.

To overcome this problem, one possible breeding strategy would be to establish a proactive rather than reactive breeding program. Insect geneticists can "force" biotypic differentiation of aphid populations, thereby increasing the biotypic variation of the aphid through breeding, selective pressure, or through foreign aphid collections. The resulting collection of aphid biotypes could then be genetically "fingerprinted" and their biology characterized. These biotypes would then be used for screening to identify new sources of resistance. This approach would result in a catalog of aphid biotypes with corresponding resistance genes that would be transferred into a series of adapted germplasm ready for release. Under this system, when aphid biotype differentiation is first detected in a given production area, the biotype would be "fingerprinted," the corresponding biotype in the catalog would be identified, and the resistance genes for that given biotype would then be available for immediate backcrossing into local cultivars.

The system described above has been put to practice against the greenbug (Puterka 1989) and is one of several strategies that can be formulated to enhance a breeding program for developing aphid-resistant germplasm. However, all strategies formulated must rely on basic information on the genetics, biology, and virulence mechanisms of the aphid. Likewise, basic information on the plant's physiological and biochemical damage response, and the molecular and cellular mechanisms and genetic control of resistance must be a high priority research effort. The development and application of marker systems—e.g., restriction fragment length polymorphisms (RFLPs), insect stress proteins, cloning of single genes, and the progress being made in transformation systems in cereals—make the future of improving single gene traits, such as aphid resistance, very exciting.

Plant resistance, cropping practices, and greenbugs

The use of resistant cultivars is a basic strategy for the management of insect populations. Generally, resistant cultivars tolerate aphids well and suffer less feeding damage. Most resistant cultivars are not totally antibiotic or immune to infestation, so aphids are not eliminated or prevented from feeding. Therefore, damage to wheat can still occur (Burton et al. 1985), but at a reduced level. Field population levels of greenbugs in wheat can be managed further by using reduced tillage practices (Burton and Krenzer 1985); populations can be reduced as much as ten-fold on susceptible cultivars, reducing them to below economic levels. Crop residues and undisturbed soil that result from reduced or no tillage provide reflective surfaces that influence greenbug flight behavior and host finding (Burton et al. 1987).

Apparently, alighting immigrant greenbugs are repelled by the shorter light waves (i.e., ultraviolet) that are associated with no-till surface conditions, and this masks the attractiveness of host plants. As a result, the influx of

immigrating aphids is reduced and the growth of subsequent populations is slowed. The influence of reduced tillage on greenbug densities is similar to the responses by other aphids to various reflective surfaces (Kring 1972). Burton et al. (1990) showed that these cropping practices are highly compatible with host plant resistance in a wheat-sorghum cropping system study. A no tillage practice in sorghum reduced the amount of greenbug damage sustained by the resistant cultivar by as much as 50% when compared with the resistant cultivar grown under the conventional (plowed) tillage practice. As a matter of fact, complementary effects were seen between the resistant cultivar and reduced tillage practices. The use of resistant cultivars combined with reduced tillage can reduce greenbug populations below economic levels, and thus, eliminate the need for chemical control. Therefore, these practices could serve as key components in a management system and reduce production costs and environmental problems.

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Resumen

Los áfidos son una de las plagas más destructivas del trigo en todo el mundo. Los métodos actuales para combatirlos se basan principalmente en los insecticidas, insumos de costo elevado que además resultan peligrosos para el ambiente. El uso de variedades resistentes a los insectos es una de las alternativas más convenientes al empleo de insecticidas y es también un componente clave del sistema de manejo integrado de las plagas. Al intensificar la capacidad innata de la planta para tolerar las infestaciones por insectos y utilizar la variedad mejorada en combinación con nuevas prácticas de cultivo, hemos podido reducir el daño provocado por las plagas y disminuir el empleo de plaguicidas. No obstante, la generación y lanzamiento de variedades resistentes de trigo sigue siendo fundamental en vista de que se están detectando nuevas plagas de áfidos y nuevos biotipos de éstos que superan la resistencia. En este trabajo se analizan métodos y problemas relacionados con el mejoramiento de trigo para obtener resistencia a los áfidos.

Integrated Pest Management: Aphid Control in South America

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Abstract

Aphids often reach injurious economic thresholds when they invade new regions or when changes in farming practices occur. The first reaction of farmers is to use chemical control, however, repeated chemical treatments can create serious problems themselves. It is necessary to develop and implement a more permanent and safer control system that relies on recommended selected pesticides only when threshold levels or critical densities are reached.

After determining the economic threshold for different aphid species, areas, etc; monitoring surveys that utilize frequent sampling should be conducted. As the wheat agro-ecosystem has its own unique characteristics, knowledge of the wheat plant itself is necessary in assessing the real impact of the pests. It is critical to remember that aphids can be important disease vectors as well. To achieve permanent solutions, an integrated pest management (IPM) program must be based on a flexible, biologically orientated approach—classical biological control being the main component. Natural enemies can be reared and released in large numbers. Farmers should avoid excessive plowing, burning, herbicide use, etc.; they should provide and manage reserves or refuges for natural biocontrol agents (i.e., hedges, bushes, intercropping, cover crops). Other strategies described include resistant cultivars, spraying of selected aphicides, and cultural and habitat management.

The South American IPM program, which provides an excellent example of permanent aphid control through the use of biocontrol agents, is discussed. It saves more than US$ 110 million per year for the five countries involved. Introduction of aphidophagous exotics is recommended for warm areas of the world.

Main Wheat Aphid Species of South America

The main aphid species recognized in South America during the first quarter of the 20th century were the greenbug, *Schizaphis graminum* (Rondani) (*Sg*), and the bird cherry oat aphid, *Rhopalosiphum padi* (L.) (*Rp*). Within the last 24 years, three additional species have been recorded: the rose grass aphid, *Metopolophium dirhodum* (Walker) (*Md*), in 1966; the English grain aphid, *Sitobion avenae* (F.) (*Sa*), in 1967; and the Russian grain aphid, *Diuraphis noxia* (Mordvilko) (*Dn*), in 1987. These three species were found first in Chile, then in Argentina, and later in Brazil. The Russian aphid is now distributed throughout the wheat areas of Chile, but, fortunately, there is still no need for chemical treatment. Most likely, these three species were accidentally carried by humans in transit from infested areas in Europe and the Near and Middle East (Zúñiga 1986)—thus escaping the adapted and effective bioregulators that suppress them in their native habitats (van den Bosch 1976). By escaping natural suppression, combined with the continuous cereal cropping systems in South America and the presence of graminicolous grasses and pastures, these species soon attained

great numbers and impact. On the positive side, native and endemic predators and pathogens had been adapting to the aphids.

The high levels attained by these three species contrast the subeconomic levels of *Rp* and *Sg* in Chile, where very many adapted parasitoids and predators kept their populations under complete control. This fact provided encouragement for undertaking a biocontrol project for *Md*, *Sa*, and *Dn*. Despite the relatively stable agricultural systems, the *Sg* population in northern Argentina and Brazil reached high densities requiring chemical spraying. Worth noting is that Uruguay usually had the same pattern of attack, but after a biological control program was started against these cereal aphids, most farmers in this region stopped spraying.

Towards a New Concept of Pesticide Use: A More Ecological Point of View—Integrated Pest Control

Apparently, pesticides have been considered by farmers to be a panacea to overcome all pest problems. Nowadays, the goal for insect management is an ecologically sound, economically viable program that provides farmers with clear guidelines for making decisions about control options (Power 1987). Now greater concern for the environment is leading to more critical acceptance of proposals for agricultural development that will lead to increased emphasis on nonchemical control measures (Greathead 1988).

This has stimulated interest in integrated pest management (IPM). The Food and Agriculture Organization (FAO) Panel of Experts on IPM defined IPM as "a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest populations at levels below those causing economic injury."

Flint and van den Bosch (1977) spelled out important aspects of this philosophy:

- A managed resource is considered to be a component of the functioning ecosystem where actions are taken to restore, preserve, or augment checks and balances in the system.
- Economic injury levels are used as decision making criteria to assess the importance of the pest species.
- The whole ecosystem is considered in the decision making process—not just the pest species (El Titi 1986).

Setting Up an IPM Program

The guidelines of Flint and van den Bosch (1977) should be considered when initiating an IPM Program:

- Understand the biology of the crop. How does the crop respond to stress? What is the plant species' growth rate under various environmental conditions?
- Identify the key pests, know their biology, recognize the damage they inflict, and initiate studies on their economic impact.
- Identify the key environmental factors that impinge (favorably or unfavorably) upon pests in the ecosystem. Determine the factors that limit survival, development, and reproduction of the key pests. Major limiting factors usually include natural enemies of the pest, which often exert more intense pressure on the pest population as it increases in abundance

(density dependence). Temperature, water availability, photoperiod, shelter, and other abiotic factors may also limit pest populations.

- Consider methods and materials that, in concert, will help permanently suppress or restrain pest species. A pest's impact can be permanently diminished by reducing its equilibrium.

IPM Options

IPM programs employ a variety of tactics—in a concerted and nondisruptive manner—to obtain effective long lasting pest control.

Biological control

Biological control is a regulation of populations that utilizes the antagonistic, interspecific interactions among them (Caltagirone, pers. comm.). Parasitoids, predators, and entomopathogens, which obtain their food supply from the pest species, are the main regulatory organisms. These antagonists must be preserved and augmented. In what is called classical biological control, the antagonistic species (bioregulators) are imported, reared, and released into the pest species' environment.

Genetic control through resistance breeding

Manipulation of the genetic make-up of the host plant so that it can resist pest attack is one breeding option. Manipulation of the genetic make-up of the pest itself so that it cannot survive in the host plant's environment (autocidal techniques) can be another successful strategy.

Cultural controls

Cultural controls involve the modification of farming practices that make the environment less favorable to pest reproduction, dispersal, and/or survival. These practices, often employed in conjunction with each other, can include: removal or destruction of the pests' breeding, refuge, and overwintering sites; crop rotation; tillage practices; planting time adjustments: harvesting practices; water and fertilizer management; and reduced use of herbicides.

Cultural control can also involve habitat management that employs trap crops, which attract pests to an area where they can be easily destroyed through spraying or other methods; habitat diversification and intercropping; and cover crops.

Chemical control

Wise and selective use of pesticides will often have limited side effects on beneficial species and wildlife. Time of application, dosage rates and application techniques are important aspects of this controversial control method.

Quarantine and regulatory controls

Strictly enforced quarantines can sometimes prevent introduction of new pest insects or at least delay their arrival into an area.

Characterization of the Wheat Ecosystem

To devise an ecologically sound program of pest control, the main characteristics or elements of the agroecosystem involved should be defined. Southwood and Way (1970) identified some of the major elements of the wheat ecosystem or cereal agroecosystem in general:

- Since the wheat agroecosystem is temporal, rather than permanent, farming operations greatly affect the survival of polyphagous predators (El Titi 1986) and parasitoids (pupae, etc.) located on the soil surface. Currently, more than 50% of all parasitized aphids are found on the soil surface (Zúñiga et al. 1986).

- Common farming practices often result in young plants being surrounded by bare ground, which makes them more attractive to aphid invaders.

- Planting arrangement and the composition of the crop stand can have dramatic effects on pest population dynamics. Seeding density affects the spread of both soilborne and airborne pathogens and influences the colonization process of various insect pests, including virus vectors (Power 1987). Perhaps one of the most important features in the crop habitat favoring the development of outbreaks of phytophagous species is the continuity of large numbers of plants with a minimum of exposure to the hazards of dispersal.

- Modern herbicides help narrow vegetation diversity by eliminating weeds, which favors the spread of diseases that can affect the life span and performance of pest bioregulators and remove alternate hosts and adult food sources of parasitoids (Zúñiga 1988). In addition, large areas of crop cultivars with narrow genetic diversity are often more attractive and/or favorable to certain pests.

- To maximize crop production area, many hedges, tree groves next to fields, and shrubs have been removed, which has drastically reduced the refuges of natural enemies of insect pests.

General Considerations for Controlling Aphids in a Wheat Ecosystem

Aphid outbreaks can be effectively suppressed by techniques that directly affect population density by destroying an increasing proportion of the population as density rises. To accomplish this, bioregulators must be incorporated or augmented into the ecosystem.

Aphid populations in wheat can be kept under control by:

- Reducing farming operations such as plowing, disking, and burning. Keep in mind that burning stubble and plowing are fatal to aphid predators and parasitoids.

- Spraying field border sites before the aphids move into the field (Klingauf 1988). Some cereal aphid species start their invasion of a field crop at protected borders made up of trees, bushes, etc.

- Reducing the number of aphids that arrive in the crop and limiting their development rate and time available for reproduction.

- Saving and promoting beneficial species. This can be accomplished by creating and conserving natural refuges such as hedges and bushes on headlands and other uncultivated areas and by maintaining green covers and establishing intercropping and strip farming. If possible, provide food sources for the nonentomophagous stages of the bioregulators. To evaluate the effect of surrounding flora, Vargas (1976) compared areas with plant stands to those with only bare ground next to a wheat field in Chile. It was found that bare soil favored aphid populations by attracting more aphid invaders and by permitting air currents to affect the epizootics of entomopathogens. The area covered with brassicas attracted more predators, mainly syrphid flies, during

the flowering stages. Wheat close to the brassicas had abundant syrphid larvae and low aphid populations. Keeping soil under green cover as long as possible is an important practice. Clover sown in winter wheat has increased the mortality of *Md*, mainly caused by entomopathogenic fungi and a population of *A. dorsalis*, an aphid predator, which was found to be high in such fields. Green manure crops, such as fodder radish (*Raphanus sativus*), can also be effective (El-Titi 1986). A procedure in Chile, using fennel as row edges, provides an important place for multiplication of predators and parasitoids (Zúñiga 1988).

Ecologically acceptable use of pesticides. Pesticides, which kill a fixed proportion of a population, are not in themselves able to regulate a pest (Southwood and Way 1970). Using selective pesticides that are harmless to important predators or parasitoids can obtain ecologically acceptable and economically viable aphid control. The rational use of pesticides through surveillance is possible only with early warning systems, which are key components of any IPM program. Spraying of selective chemicals can be effective when aphid threshold levels are reached due to ineffective bioregulator populations. Aphicide applications may temporarily suppress an aphid population, but will not solve the problem in the long term because of the homogeneity of wheat fields, the dispersal of aphids from other fields, logistics of treating large fields, and the costs related to the relatively low profits of wheat production.

Selectivity of Pesticides Against Cereal Aphid Bioregulators

Studies on selectivity can be divided into two main groups:

- Experiments that evaluate aphicide toxicity by determining the effect of different doses on different life cycle stages of the predators or parasitoids.
- Evaluation of application methods, some of which may not affect aphid predators or at least affect them to a lesser degree.

According to Zúñiga (1974, 1976), preference should be given for lower doses of recommended aphicides because they permit the survival of bioregulators that will in turn attack any new aphids invading the crop.

Zúñiga (1974, 1976) and (Irribarra 1975) discuss application methods for nonselective aphicides. When spraying by aircraft, it is suggested that unsprayed 5-m strips be maintained between the aircraft passes to allow for predator survival. And as mentioned earlier, spraying a medium or selective product over border areas where aphids first arrive before entering a field is an effective practice. Soil application of granules avoids the elimination of beneficial insects that are found in plant tillers.

When aphids start their invasion of a wheat field at the beginning of the season, they are able to increase their population before the arrival of their natural enemies, which, in turn, usually cannot suppress enough of their prey to avoid critical aphid densities. In such cases, the

goal should be to "produce" a new, effective aphid:predator ratio. For example, it has been demonstrated (Table 1) that coccinellid (*Coccinella punctata*) adults consume, on average, 48 aphids per day. If the aphid:coccinellid ratio is, lets say, 100:1, then, in the absence of other effective bioregulators, the aphid population will probably continue to increase. Now, chemical spraying might produce a certain degree of control that permits the coccinellids already present to keep the aphid population at a low level. For example, if chemicals changed the aphid:coccinellid ratio to 40:1, then the aphid population could be kept under control. An ideal selective material does not eliminate all of the target species, but allows some to survive so that the natural enemies will not starve.

Figure 1 summarizes the factors to consider in an IPM system. Wider arrows imply more importance for a particular activity.

Biological Control of Cereal Aphids in South America

During the 1967-74 period, Chile was the first country to initiate a classical biological control program for cereal aphids. Later, Chilean specialists assisted their Brazilian counterparts in implementing a similar project.

Outbreaks of *Md* in Chile caused great confusion among farmers and extension specialists because aphid infestations in cereals had never before been serious enough to justify pesticide application (Zúñiga and Suzuki 1976). At the same time, these outbreaks motivated chemical companies to mount an intense propaganda campaign for the use of pesticides. In addition, a resolution from the Ministry of Agriculture made it compulsory to control the aphids in all small grain fields in the country. Ultimately, this resulted in an increase of pest levels, which in turn resulted in

Table 1. The consumption of aphids by their various predator insects.

Predatory species	Prey species	Predator stages	Per day consumption	Author	Year
Coccinella septempunctata	*R. padi* S. avenae	adult	48	-	-
	S. avenae	4th instar larvae	40	-	-
	M. persicae	larvae			
	M. persicae	larvae	76	-	-
Syrphus ribersisi	*M. persicae*	larvae	52	-	-
Syrphus octomaculatus	*S. avenae* *M. dirhodum*	last instar	368	Zúñiga	1974
Hippodamia variegata	*S. avenae* & *M. dirhodum*	larvae	12	Zúñiga	Unpublished

farmers applying pesticide at least every 3 weeks to keep the aphid densities sufficiently low. In most cases, broad spectrum pesticides were applied at rates higher than necessary, resulting in the virtual elimination of the aphids' natural enemies.

Due to the concern of specialists from the Agricultural Research Institute (INIA) and the Universidad Austral, a National Advisory Committee on Cereal Aphids was appointed. Van den Bosch (1976) laid out the basic plan for a biological control program.

In Brazil, from an ecological point of view, there were three different situations:

- In Mato Grosso do Sul and São Paulo States, the predominant species is *Sg*; in these areas, plant breeding and biological control have been emphasized.
- In Paraná and Santa Catarina States, two species of cereal aphids were very abundant and biological control did not work until the application of broad spectrum pesticides was discontinued in 1987. Research efforts were directed toward determining effectiveness of aphicides and the ecology and bionomics of the aphids.
- In Rio Grande do Sul State, main research endeavors until 1976 included studies of pesticide effects and timing of application. In 1978, an IPM project was started with major emphasis on the biological approach.

Figures 2 and 3 present the impact of chemical control and insect management on the aphid populations of two regions in Chile and one in Brazil. Impact can be evaluated by comparing aphid density levels through the years when different approaches were undertaken. Normally, it

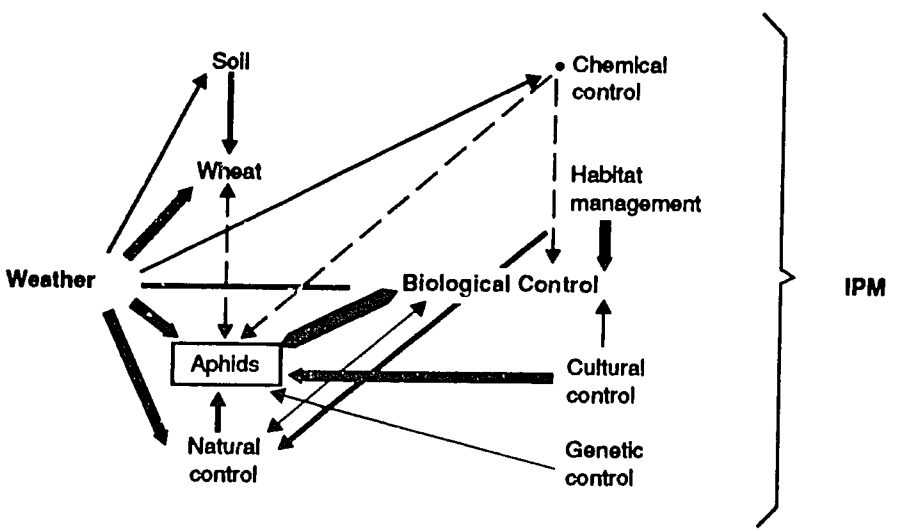

Figure 1. Factors for consideration in an Integrated Pest Management System.

took about 7 years in each Southern Cone country (Argentina Brazil, Chile, Paraguay, and Uruguay) for researchers to come to the conclusion that relying upon wide spectrum pesticides was not a sustainable approach ecologically and uneconomical as well. Particularly in Eastern Seaboard countries, the abuse of chemicals was extreme. Many unsafe mixtures and rates were tried—even using ingredients such as DDT, malathion, chlorpyriphos, and parathion. Official recommendations were to spray soon after appearance of the first aphids. In Brazil until 1980, spraying was recommended when 10% of the plants were infested with one aphid, and again after the first colony was observed, and repeating as many times as colonies were observed in the future. As wheat was a government-subsidized crop, farmers had no economic concerns about treatment expenses, so they usually sprayed two to seven times per season. Such an ecological and social disaster moved officers of FAO and the United Nations Development Programme (UNDP) to search for a new strategy. The Brazilian Agricultural Research Enterprise (EMBRAPA) became interested in starting a wheat pest management scheme that had a large biological control component.

A large-scale production system for predators and parasitoids was established. Argentina reared a total of 11,000,000 parasitoid specimens; Brazil released 1,000,000 through 1980; Chile released 7,500,000 parasitoids and 500,000 predators.

An evaluation of the degree of control and aphid abundance was conducted for 10 years in Chile, 3 years in Brazil, and a

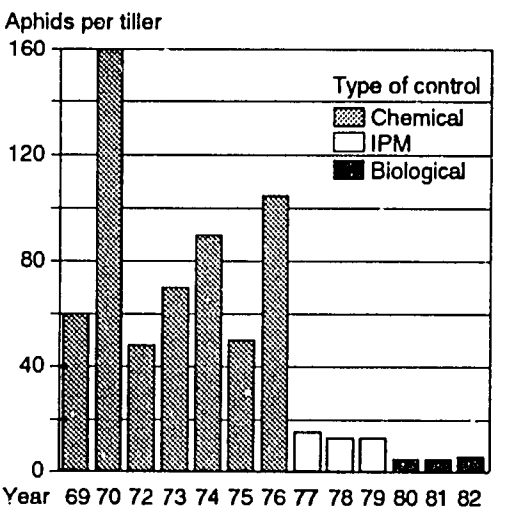

Figure 2. Annual peaks of the populations of *S. avenae* and *M. dirhodum*, Region VIII, Chile, as affected by insect management method.

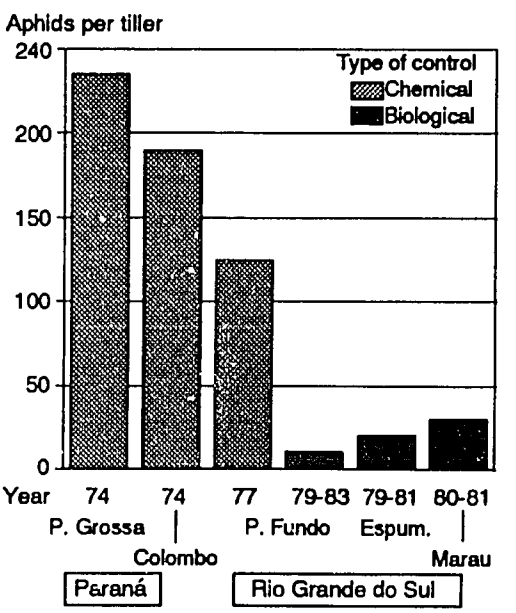

Figure 3. The effect of chemical or biological control methods on the annual peak of aphid populations in Brazil.

preliminary evaluation was carried out in Argentina. The results show that, in these countries plus Uruguay and Paraguay, *Md* and *Sa* were completely controlled. In the state of Paraná (Brazil), broad spectrum chemicals were still sprayed regularly until 1986, hindering the establishment and/or the action of effective parasitoids against *Md*, *Sa*, and *Sg*. In 1980 in the state of Rio Grande do Sul (Brazil), where an IPM program had been established, only a few wheat growers were still spraying, and so complete biological control was achieved. By comparison, in Paraná, where there was no IPM program until 1986 and 95% of the farmers were still spraying insecticides, there was no sustained aphid control. However, when farmers reduced spraying in 1987, parasitoids became established and substantial to complete aphid control has been achieved ever since.

In Argentina, the aphid population dropped from a peak of 80 *Md* per tiller to less than 2 per tiller during the 1974-1980 period. Finally, Uruguay and Paraguay have benefitted from the natural dispersion of parasitoids that crossed the borders from neighboring countries and now their cereal crops are free from economic aphid damage.

By counting the number of parasitoid larvae in dissected aphids, high levels of parasitism on aphids have been found in various locations. This supports the hypothesis that the introduced parasitoids were a main factor in creating new cereal aphid:natural enemy ratios. Furthermore, surveys revealed that the levels of parasitism in colonizing individuals arriving in the crop and in migrating individuals at the end of the season were increased to the point that it was not possible to find surviving aphids during the summer in Brazil (Zúñiga 1982).

Surveys were conducted in Brazil and Chile to determine the new levels of cereal aphids present in reservoirs other than cereal fields or cultivated pastures. These showed that aphid populations had dropped drastically in the Andean Mountain vegetation where they survive during summer and part of autumn and on gramineous plants along the borders of the rivers of Rio Grande do Sul in Brazil (Quiroz et al. 1986, Zúñiga 1982). In spite of the abundance of possible grass hosts of BYDV in the Andes, only a low percentage have been found to be infected with BYDV. This correlates with the substantial decrease in cereal aphid populations in the region, suggesting that the natural enemies introduced to control the aphids had an indirect influence BYDV occurrence.

Table 2 shows estimates, on the conservative side, of the annual cost savings of replacing two annual insecticide applications with biological control efforts in the Southern Cone of South America.

Table 2. The estimated annual cost savings (US$'000) in insecticides following the introduction of biological control in five South American countries.

Brazil	63,000
Argentina	28,000
Chile	18,000
Paraguay	6,400
Uruguay	360

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Resumen

Los áfidos a menudo alcanzan un nivel en el que provocan daños económicos cuando invaden regiones nuevas o se introducen modificaciones en las prácticas de cultivo. La primera reacción de los agricultores es usar métodos químicos; sin embargo, los tratamientos químicos repetidos pueden a su vez crear problemas graves. Es necesario idear y poner en práctica un sistema de control más permanente y seguro que utilice los plaguicidas recomendados sólo cuando se llega a cantidades liminares o a densidades críticas de áfidos.

Después de determinar el umbral de pérdida económica en relación con diferentes especies de áfidos, zonas, etc., se deben efectuar encuestas de vigilancia que utilicen el muestreo frecuente. Como el agroecosistema del trigo tiene características particulares, es necesario conocer la planta de trigo misma para evaluar el efecto real de las plagas. Es fundamental recordar que los áfidos también pueden ser vectores de enfermedades importantes. Con el fin de lograr soluciones permanentes, un programa de manejo integrado de las plagas debe basarse en un criterio flexible y orientado biológicamente, en el que el control biológico clásico sea el componente principal. Se pueden criar depredadores naturales del insecto y liberarlos en grandes cantidades. Los agricultores no deben arar en exceso, ni hacer uso excesivo de la quema o de herbicidas, etc.; deben también proporcionar y manejar reservas o refugios (es decir, setos, arbustos, cultivos intercalados y cultivos de cobertura) para los agentes naturales del control biológico. Otras estrategias descritas incluyen la utilización de variedades resistentes, la aspersión de determinados aficidas y el manejo de los cultivos y el hábitat.

Se examina el programa sudamericano de manejo integrado de las plagas, que proporciona un ejemplo excelente de control permanente mediante el empleo de agentes biológicos. Este programa permite ahorrar más de US$110 millones al año en los cinco países donde se lleva a cabo. Se recomienda la introducción de insectos afidófagos exógenos en las zonas cálidas del mundo.

Wheat Crop Management in the Warmer Areas: A Review of Issues and Advances

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Abstract

The management of wheat in the warmer areas differs from that in the more temperate areas due to the effects of climate on many aspects of the crop's environment. Also, as the wheat crop is generally not the major crop in the cropping systems of the warmer areas, its management must be adapted to the necessities of the other components of the systems. The direct effects of higher temperatures on the crop are largely due to proportional increases in the rates of biological processes with temperature. This includes the development rate of the wheat crop, leading to a shorter cropping season and the need for more precise timing of management options. The effects of higher soil temperatures on early crop development appear marked and deserve further study. Most diseases, insects, and weeds have optimum temperature ranges, and therefore the wheat crop is exposed to some new pests in the warmer areas. Chemical control of these pests has been practiced, but more attention needs to be paid to cultural control, especially of diseases and insects. The interactions between pest damage and other management practices is generally little understood, although there are some important examples of such interactions. The preponderance of highly leached, acid soils in the warmer areas leads to frequent problems of mineral deficiencies and toxicities. These become more marked as other limitations to crop yield are removed, and cropping intensity is increased. The rate of decomposition of crop residues and soil organic matter is also proportional to temperature, and their oxidation is further accelerated by tillage, leading to soil structural weakening and problems of compaction, surface sealing, waterlogging, and erosion. Solutions to many of the problems are being researched, with work concentrated in those countries of the warm belt where wheat is an important economic crop. However, given the complexities of many of the above problems, and the multiple interactions between their components, more research is needed, with emphasis on long-term multi-disciplinary research. This is especially needed to stop or reverse the degradation of soil chemical and physical fertility.

Introduction

Wheat is a new crop to the warmer areas and, as such, has little history of agronomic research in these climates. The fact that it is a new crop also means that, generally, it is not a high priority crop for often over-extended national agronomic or crop management research programs and, therefore, may receive few of the scarce research resources. It follows that those areas where wheat is an important economic crop tend to have conducted, and be conducting, most research. As in other climates, at the outset more emphasis is put on varietal production than on management research—a logical choice, as, until there are adapted varieties, meaningful agronomic research is impossible. Experience in crop management research tends, therefore, to be shorter than that in breeding. This review, or, probably more correctly, synthesis, is an effort to set the stage for the papers on crop management during the remainder of this conference.

There are few sharply defined differences between the management of the wheat crop in the warmer areas and its management in the more traditional cooler areas—and, indeed, there is no reason to expect marked differences. When wheat was, or is, introduced into a warm area, it was with the normal management practices for the cooler areas, with, perhaps, a few modifications based on experience with the warm area crops. Over time, changes or adjustments have been made in some components of the wheat crop's agronomy in some of the warmer environments, and often research results suggest that further changes may prove beneficial. All differences in crop management between the cooler and the warmer areas are, we believe, due to one or more of the following factors:

- Direct effects of higher temperatures on the wheat crop.
- Effects of climate on wheat crop pests (i.e., diseases, insects, and weeds).
- Effects of warm climate cropping systems.
- Effects of climate and cropping systems on soil chemical fertility.
- Effects of climate and cropping systems on soil physical properties.
- Interactions between the above.

As well as researching those aspects of crop management that differ from the more temperate areas, work must also be conducted on aspects and problems of production agronomy that are shared with the temperate areas (e.g., weed control of common species, management of nutrient deficiencies, management of saline areas, etc.). However, we will concentrate on those issues more particular to the warmer areas.

Direct Effects of Higher Temperatures on the Wheat Crop

Within fairly narrow limits, the duration of each stage of development in spring wheat varieties insensitive to photoperiod and vernalization can be expressed in terms of day degrees. The base temperature for the calculation of this "thermal time" appears to increase during the crop cycle from about 2°C at germination to about 9°C during grain filling (data quoted by Fischer 1985). In general, therefore, the duration of each stage of development is inversely proportional to temperature. As pointed out by Rawson (1988) on the basis of phytotron experiments, this is not a handicap provided that radiation is increased proportionately and nutrients and water are freely available. However, radiation does not increase in parallel with temperature in the warmer areas and there is little effect of temperature on the rate of net photosynthesis, with a result that growth per developmental stage and yield potential are reduced. The photothermal quotient (PTQ), the relationship between radiation and temperature is, therefore, closely related to yield under otherwise nonlimiting conditions (Rawson 1988), especially if calculated for critical phases in the crop's development (Fischer 1985).

Apart from the overall effects on crop growth, there are direct effects of soil temperature on the seed, shoot apex, secondary roots, root growth, and the root:shoot ratio—although these are confused by soil moisture effects. There are also climatic effects on pollen development and the fertilization process.

The maximum temperature for wheat seed germination has been quoted as 32°C (Caldwell 1984). However, surface soil temperatures in the hot areas often exceed this, and may reach 45°C or more,

and, therefore, stands may be reduced (Tandon 1985), especially with shallow seeding. Near Brasilia, stands are better when seeded at 8 cm than at 2-5 cm (D. da Silva, pers. comm.), and better at 5 cm than 2 cm in Paraguay (H. Causarano, pers. comm.). This latter observation was with irrigated wheat, and was ameliorated by mulch, which considerably reduced soil temperatures, thus suggesting that it was a direct temperature effect. In rainfed trials near Chiang Mai in Thailand, plant establishment ranged from 30-70% from 12 varieties all with greater than 90% germinability. Subsequent seedling growth studies at 30°C suggested the lines that established best had the lowest initial root and shoot growth rates.

Rawson (1988) suggests that shallow seeding should give an advantage in the warm areas as there will be more rapid emergence and earlier photosynthesis and growth. However, this will only be true if moisture in the surface soil is not a limiting factor as well. If moisture is limiting or temperatures are high at crown-root initiation, then crown root development and tillering are adversely affected. Shallow seeding increases the probability of both these situations and thus crop development has been reported as better from deeper seeding in the Philippines (Saunders 1988a) and Thailand (Jongdee and Limpiti 1988, Uttarapong and Wongjinda 1989). This is no different from observations in the traditional wheat areas of India where dry soil conditions may be a problem when secondary roots are initiated (Bhardwaj et al. 1975). However, apart from the effects on secondary roots, in the warmer areas deeper seeded crops have more tillers, bigger spikes and are generally more vigorous than shallow seeded crops. Plant emergence may be a problem, however, with deeper seeding as coleoptile length is shorter at higher temperatures (35°C) than at cooler (20°C) temperatures, and varietal differences in this character appear small at higher temperatures, whereas the genetic variability at lower temperatures is considerable (Woodruff 1985). Soil crusting also becomes more important as seeding depth is increased, as there is more time for crust formation after seeding and the effect of the crust will be greater on an emerging leaf than an emerging coleoptile.

Mulching, generally with plant residues, is a useful technique in reducing the soil temperature, and delaying the formation of a hard soil crust. Mulch reduces the amplitude of the diurnal variation in soil temperature, and also reduces evaporation, thus maintaining the soil surface moisture longer.

Partitioning of photosynthate may also be affected by temperature, especially the partitioning between the shoot and the root. Root:shoot ratios are lower at higher temperatures (Brouwer 1966) and thus total root mass and probably root exploration and volume are reduced. Different varieties have different maximum temperatures for root growth; Trouse (1978) found that roots of some wheat varieties did not elongate at temperatures above 20°C. However, in the phytotron studies of Rawson (1988), where yield was not reduced by temperature, the root:shoot ratio was not affected either. The impact of this suspected reduction in root growth and exploration on crop nutrition and moisture uptake have not been clarified. However, both crop nutrition and moisture availability appear more critical in the warm areas than in cooler areas. In general, responses of crops to applied nitrogen are low: most reports give grain yield responses of less than 10 kg of extra grain per kg of N applied (e.g., Saunders 1988a). However, there are reports of

higher "efficiencies" and so the generally small responses may be due to other limiting factors.

Weather at flowering can have important effects on pollen viability and fertilization. High temperatures (Hoshikawa 1959, Woodruff 1985), drought (Bingham 1966), high humidity and low light (Willey and Holiday 1971) as well as the combination of high air temperatures and low humidity (Camargo 1976) can all cause reduced seed set as may waterlogging. Considerable sterility was observed in the 1989-90 wheat season in Bangladesh in crops sown at the optimum date. It is suspected that this was due to high relative humidity and/or low light intensity during the flowering period: relative humidity was 90-95% at flowering this year, as opposed to the normal 70%, and radiation was low. All these factors, therefore, together with frost, are environmental hazards, the frequency and timing of which must be taken into account in variety and seeding date selection, as well as in determining the economic feasibility of the crop.

As with any climate, variety and seeding date must be matched, and designed to make optimum use of the major environmental factors, in this case low temperatures, radiation, moisture availability, and frost-free periods. Because of high temperatures at the beginning of the season, receding moisture profiles, and rapidly rising temperatures at the end of the season, optimum seeding dates may be quite precise (Figure 1). In Thailand, Bangladesh, and Pakistan, yield is reduced by 1-1.5% for each day's delay in seeding after the optimum date (Saunders 1988b, CIMMYT 1989) when nutrients are not limiting. Seeding earlier than the optimum last 10 days of November is generally not possible in those environments because of the harvest of the preceding rice crop. Thus in these environments, turnaround time (i.e., the time between crops) must be kept to a minimum. However, in the warm environment of tropical Queensland, Australia, where there is more time between summer and winter crops and the rainfall drops off rapidly after the end of February, Woodruff (1985) has shown that early seeding is beneficial in frost-free areas as pre-anthesis growth coincides with decreasing evaporative demand, rather than with increasing evaporation when seeded at the previously accepted June seeding date. This is close to what wheat farmers in Paraguay appear to do. In the frost-prone areas of Itapua and southern Alto Paraná states, most of the wheat crop is sown in late May and early June. However, further north, and in Paraná, Brazil, where the frost risk is less, most of the crop is seeded in late April and early May, thus taking more advantage of early season moisture.

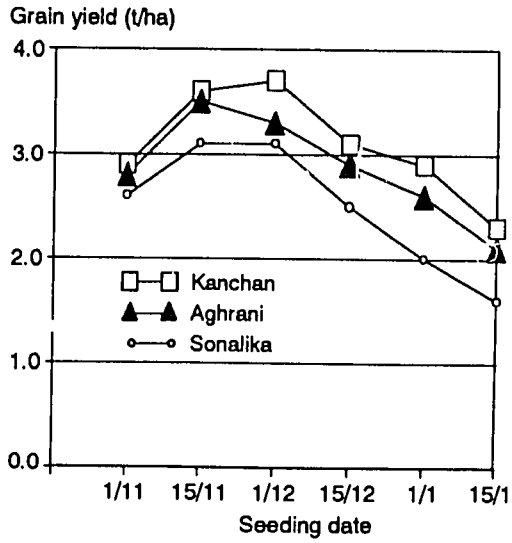

Figure 1. Mean of 11 experiments at Jessore, Jamalpur, Ishurdi and Dinajpur, Bangladesh, 1984/85 to 1986/87. Source: Saunders (1988b).

Summarizing the direct effects of temperature, it appears that temperature *per se* dictates few management changes, although soil temperature may be important for stand establishment and early crop development. Other management issues directly affected by temperature are more to do with the compressed growing season, which dictates that the timing of all management practices has to be more precise than in the cooler regions. The relatively rapid decrease in air temperature at the beginning of the winter and the rapid increase in mean temperatures at the end of the season also tend to lead to far more defined optima, especially with respect to seeding dates.

Effects of Climate on Diseases, Insects, and Weeds

During this conference several papers discuss pest problems of the wheat crop in the warmer areas, especially with respect to diseases and insects. Most of these organisms have optimum temperature ranges and thus some are a problem in the warmer areas but not in the cooler areas, and vice versa. However, as a general rule, within an organism's temperature range, its growth and reproduction rates are directly proportional to temperature, and so it tends to be more aggressive at higher temperatures.

In the recent past, most pest loss containment has relied on a combination of genetic plant resistance—especially with respect to biotic diseases—and chemical control, which has been extremely important for the control of insects and weeds, and more recently, of fungal diseases. Cultural control has been important with respect to weeds, but, until recently, there have been few examples of cultural control of insects and diseases except for the incorporation or burning of crop residues. However, there are examples of cultural control, especially with respect to one of the major fungal disease species in the warmer areas—*Helminthosporium* spp.

Seeding date may be manipulated to reduce disease incidence, especially that of *H. sativum*. Seeding date is adjusted so that the crop escapes periods of high humidity combined with high temperatures. In Bangladesh, Paraguay, and Brazil (Paraná State), where rainfall increases at the end of the season, early seeding allows the crop to escape much of these conditions at the end of the season. In Zambia, where the wheat crop is sown in summer, delayed seeding allows the crop to escape the heaviest helminthosporium infection, but leaves it prone to late season drought (Aulakh and Rimkus 1988). Also, seeding rate may be reduced and row spacing increased to give a more open canopy, reduce the relative humidity of the crop microclimate, and restrict the spread and damage due to *H. sativum* (Saunders 1988a).

Nitrogen fertilizer also can have marked effects on *H. sativum*. Observations in the Philippines suggest that N deficiency or stress predisposes the crop to helminthosporium infection, although this is not the generally accepted wisdom in Brazil and Paraguay. In a fertilizer trial in the Philippines, increasing N application rates up to 80 kg/ha reduced helminthosporium intensity, whereas above this N level helminthosporium infection increased as the crop canopy became more dense. As helminthosporium intensity is generally proportional to the crop's stage of development, it is interesting to speculate whether this was a real difference or due to the effect of N stress in speeding up the crop's

development. In Thailand, yield loss (kg/ha) due to helminthosporium was directly related to N application, but relatively (as a % loss) this became less as N supply increased (Uttarapong, unpublished data).

Many of the papers presented at the first two conferences of this series identified weeds as one of the major limiting factors to wheat production in the warmer areas. Broadleaf weeds are generally not a grave problem due to the similarity of species with the traditional areas and, as a corollary of this, the availability of relatively cheap and effective chemicals for their control. As in cooler climates, however, grass weeds are a problem, and generally the species are different from those of the cooler areas, causing a problem as chemicals for their selective control in wheat are not readily available. Perennial weeds provide a special problem, especially where no-till is contemplated. Among the most often quoted problem weeds are *Cynodon dactylon* (Bermuda grass) and *Cyperus rotundus*, a weed much more difficult to control than its cooler climate counterparts. Also, as the difference between summer and winter temperatures is less in the tropics than temperate regions, the same weed species may be a problem in both summer and winter, and rice itself may cause a problem. In the Philippines, volunteer rice is one of the major weeds of wheat. As with other areas, unless crop rotation is practiced there is a build-up of weed problems over time.

The efficacy of foliar absorbed herbicides is affected by air temperature and relative humidity, and that of root absorbed herbicides by soil temperature and moisture. Soil organic matter content, which is generally lower in the warmer areas, also affects the activity and longevity of these herbicides. Rainfall after application of many of the root absorbed herbicides affects the depth to which they are leached, and the heavy rainfall of the tropical and subtropical areas tends, therefore, to move these chemicals deeper, often into the root zone of the crop, causing wheat phytotoxicity.

Factors that affect crop stand will also affect weed competition. Poor stands due to excessive seeding depth, crusting, high soil temperatures, or other factors result in more weed problems. An interesting example comes from the Philippines. In Los Baños and Nueva Ecija, *Sclerotium rolfsii* was a major problem in one set of trials with stand losses of up to 50%. Yields, however, were not related to stand nor degree of *S. rolfsii* incidence, but were inversely related to weed incidence and competition (Saunders 1988a).

As in the temperate areas, field losses due to weeds depend on the weed population, crop yield potential, type or species of weed and the time of weed removal. There are some examples of relationships between weed populations and yields in the warmer areas (Saunders 1988a, Fessehaie et al. 1990), but, in general, population thresholds and crop losses are not well understood, making decisions on economic control somewhat arbitrary.

Effects of Warm Climate Cropping Systems

The major cropping systems, rotations or successions in which wheat is grown in the warmer areas are:

- Soybean-Wheat.
- Rice-Wheat.
- Cotton-Wheat.

Associations with sugarcane, maize, sorghum, and other crops are also found, but areas are small. Almost without

exception, wheat is not the principal economic crop in these associations, but is seeded for one of the following reasons:

- The crop fills a void in the cropping calendar for which there is no other suitable crop.
- The crop uses existing equipment, and thus effectively reduces the fixed costs per hectare per crop.
- The sale of the wheat crop provides income at the seeding time of the major crop.
- Wheat provides food at a time of shortage.

Obviously, the wheat crop must be profitable for the farmer to grow it, and this has led to subsidies on wheat or input prices in some countries of the warmer areas (and elsewhere), especially during the period when growing the crop is being fomented. However, it is important to remember that wheat is the secondary crop, and as such, it must adapt to the requirements of the primary crop, or other crops, in the association.

Apart from dictating sowing and harvest periods, and some limitations with respect to their residues, the soybean and cotton crops do not cause major problems for the wheat crop. The rice crop *per se* does not cause major problems either, except in the management of its straw, and thus in upland situations wheat may be seeded after rice with few limitations. However, because of its adaptation to flooded conditions, there are problems in following a rice crop with wheat in the lowlands. Because rice performs so well under flooded conditions, fields are kept flooded for most of the season. However, to reduce water use due to percolation, and also to support humans and animals working in the fields, hardpans are purposely formed in the paddies. Land preparation of the paddies includes puddling of the soil, which effectively breaks down all aggregates. The effects of these soil conditions on the subsequent wheat crop are discussed in the following two sections.

Effects of Climate and Cropping Systems on Soil Chemical Properties

Much of the warmer areas are covered by three soil orders: the Alfisols, the Oxisols, and the Ultisols. Of these three, the oxisols and ultisols are highly leached, low base status acid soils that represent approximately 70% of tropical America (Sanchez and Cochrane 1980), 60% of Southeast Asia (Dent 1980), and in the order of 60% of lowland tropical Africa. They are characterized by low pH and high soluble aluminum concentrations, occasionally in excess of 90% saturation of the base complex. The alfisols, which cover much of the rest of the tropical areas of Latin America, Africa, and South Asia, are chemically more fertile with a higher base status and initially without an acidity problem. However, acidity can develop on these soils with continued cultivation.

Due to the preponderance of acid soils in the warmer areas, much work has been done on the effects of liming, lime requirements, and, more recently, on methodologies for reducing Al toxicity below the plow layer. This is of great interest especially where dry periods are encountered, as otherwise roots are confined to the superficial layer where pH has been corrected by liming. The long-term effects of fertilizing these soils on the development of acidity needs to receive more attention, and in this regard, source of nitrogen will be particularly important.

Crop breeders have produced wheats with a considerable degree of aluminum tolerance from the old Brazilian wheats and a respectable yield potential from the semidwarf "Mexican" wheats. However, these cultivars function up to a maximum of about 60% Al saturation, while above this very little yield is obtained. At these low pHs and high Al saturations, phosphorus deficiency is a problem, to such a degree that some wheats, e.g. Alondra, show some field tolerance to low pH conditions—not because of Al tolerance, but due to P efficiency. In the Cerrados of Brazil, P deficiency is so marked that for the first three crops it is better to broadcast P fertilizer than to band it, after which time banding is preferable (McMahon and Goedert 1985).

It is interesting to note that triticale generally performs better than wheat in acid soils. In the case of Cascavel, Paraná, Brazil, about 25,000 ha of triticale are grown for this reason. In the East African countries of Burundi (Schalbroeck 1985) and Rwanda (A. Egli, pers. comm.), triticales commonly outyield wheat by more than 50%. Not only do triticales apparently have more Al tolerance, but also more efficiency in uptake of several nutrients.

On low pH soils, calcium deficiency is obviously a problem, although generally not for wheat. However, magnesium deficiency also appears common in Paraguay from samplings taken by the National Wheat Program and CIMMYT, and is also reported in Burundi (Schalbroeck 1985). This may be accentuated by using calcitic rather than dolomitic lime for the correction of pH, thus disturbing further the Ca:Mg balance.

As in the cooler areas, micronutrient deficiencies are being detected with increasing frequency in the warmer areas. These deficiencies are due to the inherent fertility status of the major soil types, increased cropping intensities and removal of crop residues, and the use of high analysis fertilizers without micronutrient contaminants and are being detected largely due to better diagnostic capabilities. In Bangladesh over the past years, responses have become progressively evident to P, K, Zn, and S and now there are indications that B, Mg, and Mo are reaching critical levels (Saunders 1988a). Zinc is a limiting factor in many of the acid soils of Africa and Latin America (Katyal and Friesen 1988). Zinc is also limiting in some Indian soils (Nambiar and Ghosh 1984) and in Nepal. Copper deficiency has been detected in Kenya and in Tanzania (Kamaso and Singh 1982) as well as the Cerrados of Brazil. Boron deficiency seems to be widespread with deficiencies reported in India (Singh and Singh 1976), Nepal (Sthapit et al. 1989), Thailand (Rerkasem et al. 1989), Bangladesh (D. Saunders, pers. comm.), Brazil (da Silva and Andrade 1983), Zambia (Aulakh and Rimkus 1988), and appears widespread in Paraguay.

Whereas manganese deficiency can be a problem in the lowland rice-wheat rotation on alkaline soils in Asia (Katyal and Friesen 1988), Mn toxicity can be a problem on acid soils, especially when waterlogged—a condition that can occur frequently when poor soil management causes a marked plow-sole. An example of the differential effects of different toxicities comes from East Africa. Researchers noted that the entries in acid tolerant wheat nurseries behaved differently in the Eldoret region of Kenya compared to other regions of East Africa. Soil analysis showed that at Eldoret, Mn toxicity appeared to be the major constraining factor, while at Mbala in Zambia, a site representative of most acid soil areas of East Africa, Al toxicity was the major problem.

The anaerobic conditions of the rice paddy and the change from anaerobic to aerobic conditions at the end of the rice season cause complex changes in the chemistry of these soils. It appears that the precipitation of iron may be partially in the form of insoluble iron phosphates, thus tying up some of the labile phosphate pool. In Bangladesh, no residual effect of borax applications has been observed, even when applied to the wheat crop at toxic levels. This leads us to speculate that B might also be immobilized like P in these soils.

Effects of Climate and Cropping System on Soil Physical Properties

There are four major problems of wheat production in the warmer areas associated with soil physical conditions:

- Stand reductions due to soil crusting.
- Poor root growth due to compact soils.
- Waterlogging.
- Erosion.

The common factor that appears to be the basic cause of these problems is soil organic matter breakdown, which increases with increasing temperature, and, like crop development, has a Q_{10} of approximately 2. Thus soil organic matter breakdown in the warmer areas is faster than that in the cooler areas. Coupled with this effect of temperature is the effect of tillage, which is the factor that seems to put the system out of equilibrium. As crop development is more rapid in the warmer areas and frost is not normally a limitation to cropping intensity, two or more crops are often grown per year. Generally, the soil is tilled for each crop, aerating the soil and speeding up the oxidation and breakdown of organic matter. This organic matter breakdown—especially the breakdown of the humic compounds involved in aggregate formation—leads to structural weakening of the soil (Figure 2). As aggregates are broken down, soil porosity is reduced and infiltration suffers. This, in turn, leads to more runoff and erosion, and at the same time leads to less available water for the crop, as only that portion of the rainfall that enters the soil can be used by the crop. A soil whose aggregate structure has been broken down is compacted more by traffic and implements than a well structured soil. It also needs more tillage to attain a workable tilth as it becomes blocky and difficult to manage. This compaction in turn leads to less water entering the soil below the compacted layer, restricts root growth, and leads to waterlogging in the surface layer as water is maintained above the compacted layer. On slopes, this may lead to increased erosion as the whole plow layer slides off the hillside. Tillage also incorporates the plant residues, to a degree dependent on the implement, leaving the soil surface unprotected against the energy of raindrops. Raindrops break down the surface structure, especially where it has already been weakened by tillage, pulverize the aggregates, and lead to surface sealing. This seal restricts water infiltration, again leading to more runoff and erosion and forms a crust on drying that impedes seedling emergence.

In the warmer wheat growing areas, important reductions in soil organic matter (O.M.) have been recorded. In Paraná, Brazil, the soil O.M. content of 2.03% of a cultivated oxisol contrasts with 4.95% O.M. in the virgin forest (Kemper and Derpsch 1981). In the Chaco of Argentina, original O.M. levels have been reduced from over 3% to 1.6% by many

years of cotton cultivation (Inalban and Galetto, unpublished data). In southeastern Paraguay, O.M. contents were reduced by tillage from an average 4.5% to an average 1.5% in 10 years (D. Bordón, pers. comm.). We do not know which fraction or fractions of soil O.M. are the most important, but it is likely that the humic compounds involved in aggregation are among the most important. These products of humification are developed over time, and so a soil in which the content has been depleted cannot be restored to its former fertility quickly, e.g., by incorporating one green manure crop. Analysis of total O.M. contents of soils is probably an indication of soil physical fertility only in so far as it correlates with the content of the important fractions of O.M. in the soil. This is probably true for soils where O.M. content is being reduced, but is probably not valid where the structure of degraded soils is being regenerated.

Most of Figure 2 applies to all areas equally. However, erosion is a greater problem than waterlogging in the "upland" areas, while the inverse is true in the lowland areas typical of much of the rice-wheat rotation. Of course, this is not a problem for the rice crop, and is often provoked specifically to benefit this crop, but does prejudice the wheat crop.

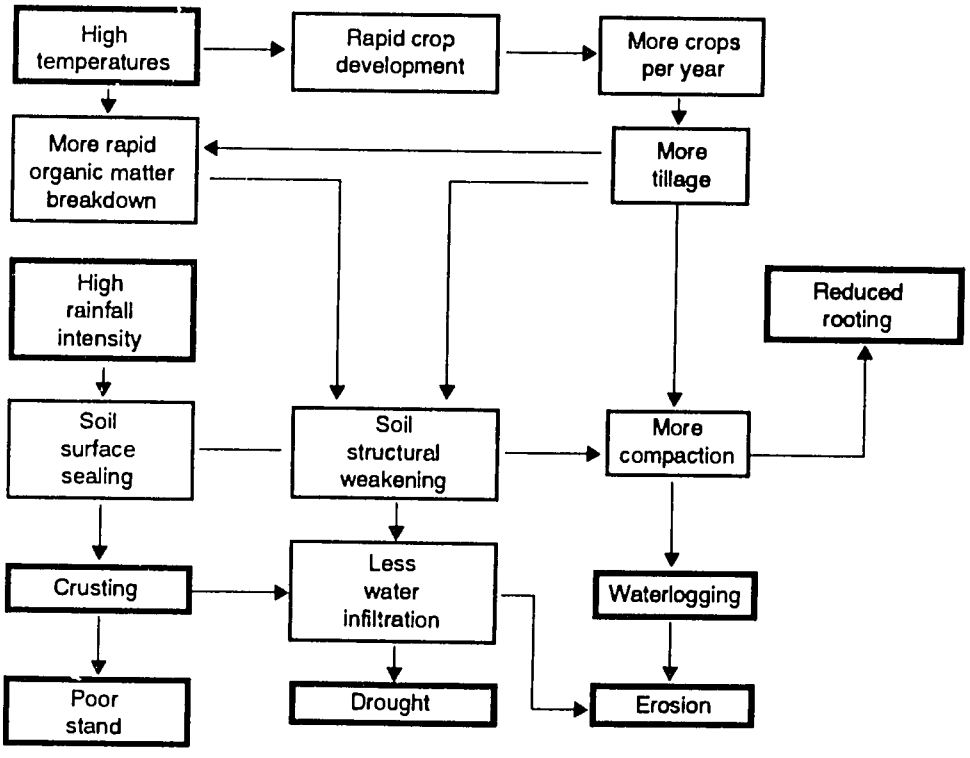

Figure 2. Inter-related factors leading to soil degradation, poor crops, and soil erosion in warm environments.

There are five major solutions being used or investigated with a view to overcoming these O.M. and soil structural problems:

- Reduced tillage.
- Mulches.
- Deep tillage.
- Green manures.
- Drains.

Since excessive tillage is one of the major causes of the O.M. crisis, much can obviously be done by minimizing tillage. Tillage is often done to produce a preconceived tilth that may have little or no validity in today's agriculture. In mechanized areas, the capabilities of the seeder are probably more important in determining the required tilth than are soil conditions or the needs of the crop. In rice-wheat areas, it is common to plow the land many times and then pass a wooden "ladder" over it several times to produce an acceptable tilth. A recent survey in one area of Bangladesh revealed that as many as 11 plowings (mean of six) followed by an average six to seven passes of the ladder are carried out (Saunders 1990a). However, the results shown in Figure 3 from Bangladesh for both "good" and "bad" seasons provide no evidence of yield benefits from all these plowings (Anonymous 1985).

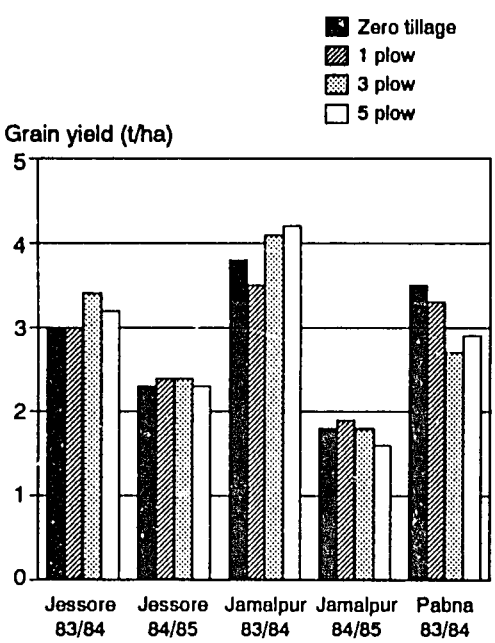

Figure 3. The effect of tillage intensity on wheat yields in Bangladesh. Source: Anonymous (1985).

No-till or zero-till (the logical conclusion of reduced or minimum tillage) has shown good results in trials in many parts of the warmer areas (e.g., Bangladesh, Brazil, Pakistan, Thailand, and Zambia). It is in widespread commercial use in the warmer areas of Brazil and more recently in Paraguay. While yield increases are not always evident with no-till, other important benefits are a reduction in tillage costs (although this may be offset by increases in costs of weed control and fertilizer) and a reduction in turnaround time between crops—a very important factor where seeding date is critical and/or inclement weather is common over the land preparation and seeding periods.

Apart from the reduction in tillage-induced damage to aggregate structure, benefits appear to accrue from maintaining root and animal channels and from an O.M. build-up in the profile (Sidiras and Pavan 1985, Maurya 1986), due, at least partially, to the slower breakdown of root residues. We suggest that, in the rice-wheat system, the maintenance of root channels from the last crop cycle is important in increasing wheat rooting depth, and may account for the improved growth of the wheat crop when this is direct seeded in the residues of a tilled rice crop.

There are some problems associated with no-till. As one of the major benefits of tillage is weed control, weeds become a more critical problem when tillage is eliminated. Infestations of perennial weeds, which are difficult and expensive to control by chemicals alone, may deter the adoption of a no-till system until they are controlled. However, in contrast to upland areas, weed problems appear to be fewer with no-till than with conventional tillage in the rice-wheat areas.

In a no-till system, compaction due to traffic can also be a problem on some soils. However, it is generally shallower than the compaction caused by tillage and is easier and cheaper to control, if necessary, with occasional shallow tine tillage. This compaction may result in reduced early plant growth. However, in general, plant roots will grow out of a compacted layer but not into one, so surface compaction does not cause as much yield reduction as a subsurface compacted layer.

Insect pests and diseases may carry over from one season to the next on the crop residues, and the use of adequate crop rotation is, therefore, more important in a no-till system. In Brazil and Paraguay, the carryover of *Helminthosporium tritici-repentis* on the wheat straw, and the resulting early infection of the subsequent wheat crop, are problems with continuous no-till wheat-soybean systems.

The full benefits of no-till will probably only be seen on undegraded land, or after several years on land that has had some structural degradation. Phillips et al. (1980) suggested that, even under the conditions of Kentucky in the USA, it takes 12 years of no-till for a soil to attain the same condition as under a pasture.

Another major problem of no-till has been seeding into the stubble or residues of the previous crop. This is no longer critical in mechanized areas where large and relatively heavy equipment can be used, but is still a considerable problem on small farms, especially where animal traction is used—as is the case of most of the rice-wheat areas of Asia. Equipment for small-scale farmers still needs to be developed, although there is apparently equipment that works well in the Jiangsu and Shantung Provinces of China (Suriwongse 1988). The International Rice Research Institute (IRRI) has developed some small equipment that appears useful in some wheat situations. Another possibility being investigated in Thailand and Bangladesh is to broadcast wheat seed onto the soil surface. Initial results suggest that this is feasible as long as sufficient mulch is maintained. In the Kushtia area of Bangladesh, broadcast seeding of wheat into the standing rice crop about 2 weeks prior to harvest also shows promise, although seeding density needs to be increased as tillering is poor. For broadcast seeding of wheat onto the soil surface, pre-soaking of the seed has been tried with positive results. Fukuoka (1977) in Japan has been relaying barley into standing rice over the last 30 years in a no-till system.

The use of mulches is the next factor being studied to overcome soil physical degradation. Mulching goes hand in hand with no-till and is probably necessary for the success of the system. In Thailand, no-till yielded the same as conventional tillage as long as mulch was retained, but if the residues were burned, yield was reduced significantly (D. Saunders, pers. comm.). The importance of mulches in stabilizing soil temperature and maintaining surface moisture were mentioned earlier. In upland areas, one of the major benefits of mulch appears to be

its effect on water infiltration (Roth et al. 1988). The plant residues protect the soil surface from the impact of raindrops and thus avoid the surface sealing. These data from Brazil suggest that, for this reason, it is preferable to grow a cover crop rather than to leave the land fallow in upland areas.

In the lowland rice-wheat areas, one of the major benefits of mulch is apparently its effect in maintaining soil surface moisture. In pulverized rice soils, this is extremely important as it delays crust formation, thereby improving stand. Mulch also improves surface moisture at the critical crown root initiation stage, thus allowing the development of secondary roots.

Deep tillage may be necessary where past tillage practices have led to the formation of compacted layers. In the Barani rice areas of Pakistan, wheat root development is restricted by a hardpan formed at about a depth of 20 cm by continued use of the country plow. Deep tillage with a moldboard plow breaks this compact layer and leads to yield increases of 30-40%. In Brazil, Paraguay, and Bolivia, hardpans formed by continuous use of heavy disk harrows are common. These hardpans reduce yield, especially in drier years, and restrict the response to applied fertilizer (H. Caceres and H. Causarano, pers. comm.). Responses to deep tillage have also been shown in Zambia (Aulakh and Rimkus 1988).

Green manures discussed by Derpsch (1991) may have an important part to play in maintaining soil physical and chemical fertility—not only because of the residues they provide, but also due to their root exploration, which is often deeper than that of the common annual agricultural crops.

In the lowland areas, one of the major problems observed in fields of wheat seeded after rice is waterlogging, due to the hardpan and to a lack of drainage infrastructure. Waterlogging is especially critical in the early crop stages, after which the crop is more resistant. Planting wheat on raised beds has given acceptable results at Phrae in Thailand. Chinese experience suggests that drainage is critical—deep, narrow drains are put at intervals in the wheat crop and linked up with peripheral drains. Rinaldo Calheiros in Londrina, Brazil, has interesting results using mole drains in wheat after rice in some planosols. These empty into peripheral drains that can also be used to bring water to the crop by subirrigation during dry periods.

Interactions

Most of the points mentioned in this paper are, in fact, interactions between several factors. The fact that some of the solutions, e.g., mulch, are considered for several different problems suggests the complexity of some of these interactions.

Crop rotation is one important factor discussed little in this paper. The inclusion of crops of different genera and growth and rooting habits can benefit physical and chemical fertility and pest and disease control. Mehta and Gaudêncio (1991) discuss the effect of rotations, especially in Latin America. In Asia, the yields of both rice and wheat are better when a legume is included in the rotation than those in a continuous rice-wheat succession. Including different crops in the rotation can break disease, insect (especially nematodes), and weed cycles.

Conclusions

The management of the wheat crop in the warmer areas is, as expected, a composite of the requirements of the different facets of the environment, including the soil physical and chemical conditions, climate, and cropping systems. As yet, most energy has been spent on overcoming the first generation problems needed to produce an acceptable crop. However, some programs have made a good start on the longer term and more basic aspects of the crop's agronomy. In the future, more emphasis will have to be placed on these issues. Such research will require more medium- and long-term trials that study the cropping system over time and record and digest its impact on productivity—present and future. This itself will involve more commitment of national research programs to this aspect of research, and often more commitment of researchers to work in truly coordinated multi-disciplinary research.

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Resumen

El manejo del trigo en zonas cálidas difiere del requerido en las zonas templadas a causa de los efectos del clima sobre muchos aspectos del ambiente del cultivo. Además, como el trigo generalmente no es el principal elemento en los sistemas de cultivo de las zonas cálidas, su manejo debe adaptarse a las necesidades de los otros componentes de los sistemas. Los efectos directos de las temperaturas altas sobre el cultivo obedecen en gran medida a aumentos proporcionales de la velocidad de los procesos biológicos con la temperatura. Esto incluye la tasa de desarrollo del trigo, que resulta en una temporada de cultivo más corta y una sincronización más precisa de las prácticas de manejo. Los efectos de las temperaturas altas del suelo sobre el desarrollo temprano del cultivo parecen ser marcados y merecen ser investigados más a fondo. La mayoría de las enfermedades, los insectos y la maleza tienen un rango de temperaturas óptimas y, en consecuencia, el trigo está expuesto a algunas plagas nuevas en las zonas cálidas. Se ha efectuado el control químico de estas plagas, pero es preciso dedicar más atención al control mediante las prácticas de cultivo, especialmente de las enfermedades y los insectos. En general se sabe poco acerca de las interacciones entre los daños causados por las plagas y otras prácticas de cultivo, a pesar de que existen algunos ejemplos importantes de esas interacciones. La preponderancia de suelos ácidos muy lixiviados suele causar problemas de carencias de minerales y toxicidades provocadas por éstos. Esos problemas se vuelven más marcados a medida que se eliminan otras limitaciones del rendimiento y se aumenta la intensidad de cultivo. La velocidad de la descomposición de los residuos del cultivo y de la materia orgánica del suelo también es proporcional a la temperatura y la oxidación de esos elementos se acelera aún más con la labranza, lo cual provoca un debilitamiento estructural del suelo y problemas de apisonamiento, encostramiento, aniego y erosión. Se están investigando las soluciones a muchos de estos problemas y la labor se concentra en los países de la franja cálida donde el trigo es un cultivo económicamente importante. No obstante, dada la complejidad de muchos de los problemas antes mencionados y las múltiples interacciones entre sus componentes, se requiere efectuar más estudios y hacer hincapié en las investigaciones multidisciplinarias a largo plazo. Esto es especialmente necesario para detener o revertir la degradación de la fertilidad física y química del suelo.

Tillage Practices and Soil Physical Degradation in the Wheat Cropping Systems of the Warmer Areas of Latin America

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Abstract

Oxisols and Ultisols are the predominant soils in the nontraditional warm areas where wheat is grown in Latin America. They are clayey soils where kaolinite, iron, and aluminum oxides are the most important minerals in the clay fraction. Cation exchange capacity is generally low and organic matter content is less than 3.5%. When soil moisture is high, these soils have a plastic and sticky consistency. The most important crop production system is a winter crop of wheat followed by soybeans in the summer. Small areas are sown to maize and cotton as an alternative to soybeans. At least four soil tillage systems are common in the areas under discussion: traditional, conventional, chisel, and no-tillage—in addition, there can be various combinations of these.

Due to the fragile tropical ecosystem, these soils can be physically degradated when inappropriate soil tillage and management systems are used. The most common problems observed are the pulverization of the topsoil structure, a hard pan below the plow layer, and soil erosion. Tillage systems involving burning of crop residues and disk machinery are particularly responsible for such problems. Soil tillage systems have various degrees of efficiency and the choice of a specific system, associated with reduced machinery use and the improvement of crop rotation systems, appears to stop or even reverse the process of physical soil degradation.

Introduction

Physical degradation of the soil in the nontraditional wheat areas of Latin America poses a serious problem for crop production and preservation of the environment. Soil compaction and erosion are closely associated with the existing production systems, especially soil tillage. Each tillage system conditions the soil surface and subsurface characteristics by acting directly on the soil mulch rate, surface roughness, water infiltration rate, water storage, aggregate stability, and soil temperature. These factors are all closely related to erosion.

The Soybean-Wheat Rotation

The major production system in the nontraditional warm areas of Latin America is wheat in the winter and soybeans in the summer. In some areas, maize or cotton is substituted for soybeans. Figure 1 shows the agricultural calendar in southern Brazil where the soybean-wheat system predominates. In the warmer areas, rainfall is high during the spring and summer months. During the winter, monthly rainfall averages less than 100 mm and severe drought can occur (Kochhann 1988). In the area north of 23°S, wheat can be grown only under irrigation.

In the cooler subtropical areas, wheat is sown later during June and July to reduce the risk of frost. Drought risks under these conditions are also reduced.

The Soils

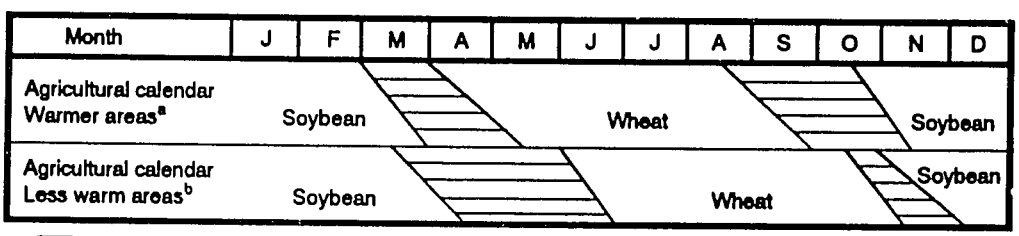
Oxisols and Ultisols predominate in most of the warm wheat growing areas, with the Oxisols making up more than 50% (Kochhann 1988). A small part of the region has some Alfisols. Generally, wheat is grown on these soils because large-scale mechanization is possible.

These soils are highly weathered and show a predominance of kaolinite and amorphous material, rich in iron and aluminum, in the clay mineral fraction. Since organic matter usually does not exceed 3.5% under tropical conditions, even in the natural state, the cation exchange capacity (CEC) is also low and highly dependent on this soil organic fraction (Pavan et al. 1985).

In the wheat growing areas, the soils are seldom less than 40% clay. In the northern and western parts of Paraná State, Mato Grosso do Sul State, and southern São Paulo State, Paraguay's Paraná River Valley, and in northern Argentina, the soils exceed 60% in clay content. The clay content, the rate of weathering, and the relatively low organic matter impart to these soils a high degree of plasticity and stickiness and a narrow friability range.

Low phosphorus availability is also a common feature in these soils, rarely exceeding 2 ppm under natural conditions. Availability of calcium and magnesium is often low as well.

Toxic levels of aluminum are also commonly found in the Oxisols, especially deeper in the soil. Many soils in these areas have either a low content or an absence of exchangeable aluminum in the topsoil, but this increases with depth (EMBRAPA/IAPAR 1984). Many breeders and farmers choose varieties based only on the fertility (determined by a soil analysis) of the arable layer. Since they often do not study soil maps nor consider the deeper soil layers, they often select varieties that are sensitive to the aluminum present beneath the top soil layer.



period available for tillage.
[a] Coolest month mean temperature: >15°C.
[b] Coolest month mean temperature: 12.5-15°C.

Figure 1. Agricultural calendar of the most common production system in the nontraditional, warm wheat areas of southern Brazil.

Common Tillage Systems

The tillage systems used in these areas can be divided into two major categories:

- Systems that disturb the arable soil layer and that leave the soil highly exposed due to low levels of crop residue (mulch) on the surface.
- Systems that do not disturb—at least not significantly—the arable layer and that leave the surface totally or partially mulched.

Systems that disturb the arable layer
Three distinct systems can be described.

Traditional—This system usually involves burning the wheat straw during August or September followed by one heavy disk harrowing and two or three light disk harrowings. The mechanical power available on most farms is only sufficient to pull the smaller models of heavy disk harrows, which have limited soil penetration capacity—seldom deeper than 15 cm.

After soil preparation, a summer crop is seeded—usually soybeans. After harvest of this crop in March-April, the soil is given another heavy disk harrowing and at least one more light disking. Therefore, the total number of workings in one agricultural year on the same soil surface is two heavy diskings and three to five light diskings. After soybean harvest, farmers have about 30 days in which to sow wheat during the optimum period. In the warmer, more northerly areas, wheat seeded after this optimum period in late May and beyond will often be exposed to higher risks of drought, frost, and disease late in the crop cycle, as well as rain during harvest. Therefore, due to its speed and relative low cost compared to other conventional systems, this traditional system is preferred by farmers.

In the more southerly, cooler areas, seeding date is less critical (Figure 1).

Conventional—In this system, less wheat straw is burned and a disk plow serves as the primary tillage equipment, which can penetrate to a depth of 20 to 25 cm. The number of passes over the field is similar to that for the traditional system. But due to the slow working speeds and high power requirements, farmers seldom use it. However, this system has the best performance where incorporation of crop residues, lime, and fertilizers is required (Garcia et al. 1981).

Combined systems—Many farmers combine the traditional and conventional systems by using the plow or heavy disk harrow in tillage for just one of the crops. Since in the warmer areas, the agricultural calendar for the winter crop is more restricted and risky, the heavy disk harrowing is more popular for seedbed preparation for the winter wheat crop.

Systems that do not disturb the arable layer
Three distinct systems can also be described for this category.

Chisel plowing—Chisel plowing replaces both plowing and heavy disk harrowing in this system. Wheat straw is not burned and remains partially on the surface after tillage. Usually, the chisel plow is set to a depth of 20 to 25 cm, although it can be set to work deeper where a plow pan is present. Fewer light harrowings are

required after chiseling since there is less soil disturbance and hence fewer clods caused by the equipment.

Farmers' use of chiseling has increased slightly in recent years, mainly due its high output efficiency (ha/day)—almost the same as with the heavy disk harrow (Hoogmoed and Derpsch 1985), and because they are aware of the problems caused by disk harrowing over the long term. Farmer acceptance has been somewhat restricted because weed control has only been fair and the power requirements required for chiseling are high.

No-tillage—The use of no-tillage, which provides more mulch for the soil, has increased significantly in high rainfall areas. However, where wheat has low yields due to low rainfall, there is usually not enough straw production to provide sufficient soil cover. Due to this and high decomposition rates during the spring, the soil is exposed resulting in weed problems (Almeida and Rodrigues 1985), reduced water infiltration and storage (Derpsch et al. 1984), increased soil temperature (Sidiras and Pavan 1986), and increased water erosion (Lopes et al. 1987a). In addition, more efficient seeding machines are required for clay soils with low organic matter, the Oxisols and Ultisols, common in these areas.

Many farmers, mistakenly, attempt to introduce no-tillage in areas that have soil compaction, high acidity, nutrient imbalances, and a wide spectrum of weeds that are difficult to control. Under many conditions, especially in clay soils exposed to a dry winter season, no-tillage has not improved these problems.

Combined systems—Some farmers have adopted systems that combine chiseling and no-tillage. Most prefer to use no-tillage for the wheat crop because of the short time between soybean harvest and wheat sowing and the better efficiency of the wheat seeding machines. Also, the wheat growing season is characterized by a low incidence of weeds, which makes the herbicide costs less expensive. After no-tillage for the winter wheat crop, farmers may chisel plow or some other method for the summer crop.

However, some farmers prefer no-tillage for the summer crop because erosion caused by summer rains is a major problem.

These conservation tillage systems are sometimes combined with the conventional and traditional systems discussed above. Table 1 summarizes some of the characteristics and performance of these various tillage systems.

Physical Soil Degradation

In tropical ecosystems, where rainfall and temperature are high, as in the nontraditional warm areas for wheat, the introduction of different soil managements can lead to rapid changes. Biological transformations are fast, as humidity and temperature favor them.

Specifically, changes in organic carbon levels in the soil relative to the original content indicate how intense the process can be. In Paraná State, wheat crop soils derived from igneous rocks and where native forests once grew, often have organic matter levels above 2.4% (EMBRAPA/IAPAR 1984). However, Mondardo et al. (1979), studying agricultural land use based on soil sampling and analyses carried out in 1978, showed that there is a tendency toward a severe depletion of organic carbon (Figure 2). Machado and Brum (1978) and Cintra et al. (1983) obtained similar results in Rio Grande do Sul State, Brazil.

Table 1. Some characteristics and performance of four common tillage systems for wheat in the nontraditional, warm areas.

Characteristic or subject	Tillage Method			
	Traditional	Conventional	Chisel	No-tillage
Tillage equipment	Heavy harrow disk	Disk plow	Chisel plow	-
Levelling equipment	Light harrow disk	Light harrow disk	Light harrow disk	-
Seeding machine	Common	Common	Double disk	Special
Weed control method	Mech. + herb.[a]	Mech. + herb.	Mech. + herb.	Herbicides
Weed control efficiency	Good	Good	Fair	Good [b]
Lime and fertilizer incorporation	Too superficial	Good	Bad	Bad
Top layer pulverization avoidance	Bad	Bad to fair	Fair	Good
Plow pan avoidance	Bad	Bad	Good	Good [c]
Erosion avoidance	Bad	Bad to Fair	Fair	Good
Root growth	Bad	Bad to Fair	Good	Fair to Good
Labor efficiency	Good	Bad	Good	Good

[a] Mechanical + herbicides.
[b] Can be expensive in some conditions.
[c] Can cause compaction in the top layer.

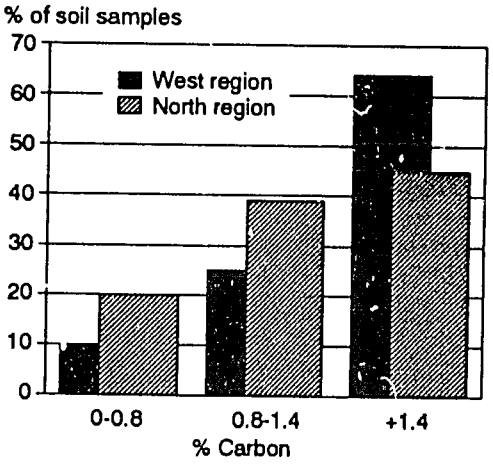


Figure 2. Content of organic carbon in soils from two different regions of the state of Paraná in Brazil. Source: Mondarado et al. (1979).

Pulverization of top layer structure

A system involving two crops each year can significantly restrict the time available when tillage operations can be carried out. As a result, farmers often till the soil without observing basic tillage principals in order to get seeding done at the optimum time. Thus, due to the soil being either too dry or too moist, farmers often pull the tillage equipment above the recommended speed to obtain adequate depth penetration. With dry conditions, this produces large clods and additional light harrowings are required to reduce them further. With high moisture conditions, the soil becomes susceptible to compaction.

Plow pan

Soils in the wheat growing areas are usually porous enough to allow adequate water infiltration and successful root growth (Kemper and Vieira 1979). However, these soils are susceptible to plow pan formation caused by the tillage equipment. Figure 3 shows the distribution of porous and solid materials in two profiles of an Oxisol. In the layer below the tillage zone, the soil presents a higher solid/volume ratio with a marked reduction of macropores volume.

Besides greater mechanical resistance, soil water infiltration is affected by this compacted layer, although Derpsch et al. (1984) observed that mulching is the factor most related to infiltration.

Several studies have shown that root growth is reduced by compaction (Taylor 1974, Russel and Goss 1974, Vieira et al. 1978, Vieira 1981a, and Coale and Grove 1986).

Figure 4 presents the relationship between mechanical resistance and wheat root growth in Oxisols. When there is a pulverized layer above the plow pan, wheat root systems are shallow, exposing the crop to greater risks. Figure 5 shows the behavior of root density in the disturbed top layer as the soil resistance gradient between the surface soil and the plow pan layer increases. Wheat root density in the upper 10 cm increased relative to the total root system as the resistance gradient between the two layers increased. Although this behavior requires further research, the structural gradient seems to be an important factor in the determination of the root growth pattern. Similar behavior was observed in soybean crops by Koepke and Vieira (1981) as cited by Vieira (1981a).

Besides mechanical resistance values that increase as the soil loses moisture (Taylor 1974), other aspects also contribute to reducing root growth in compacted layers.

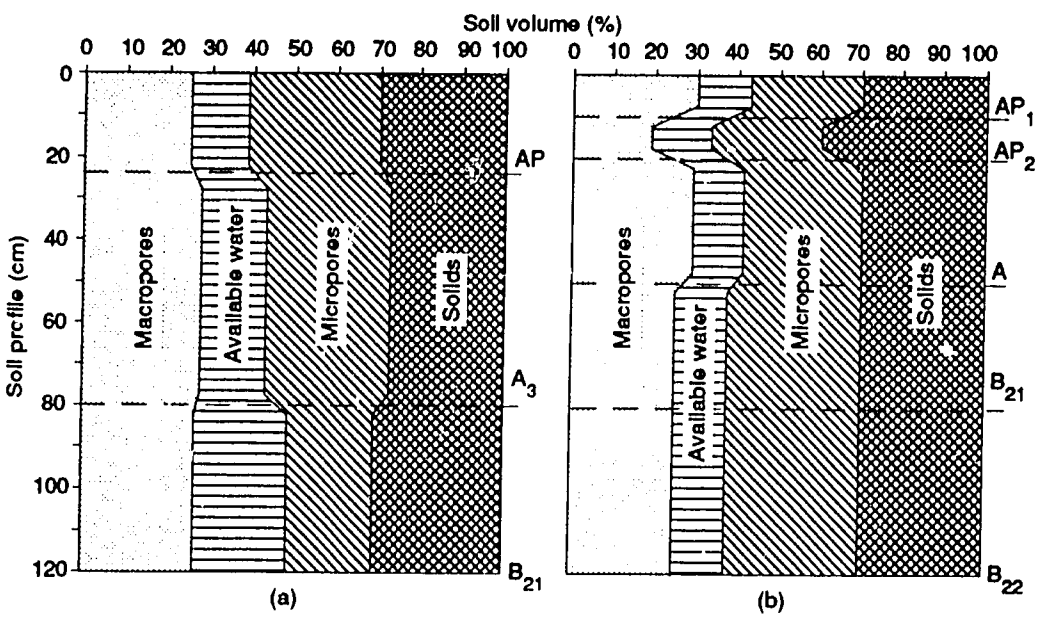


Figure 3. Soil porosity distribution in two Oxisol profiles under native pasture (a) and intensive mechanization (b). Source: Kemper and Vieira (1981).

For example, in wet periods the air space in these layers may be reduced to critical levels for plants that are more sensitive to low oxygen levels in the soil (Vieira and Muzilli 1984). However, for oxygen to be depleted significantly in Oxisols and Ultisols, high rainfall and excessive soil compaction are required.

In addition, where soils are compacted, it is difficult to incorporate lime fully through the topsoil and thus high aluminum concentrations can contribute further to poor root growth. Vieira and Oliveira (1985) observed the influence of compaction and aluminum concentration on soybean root growth under controlled

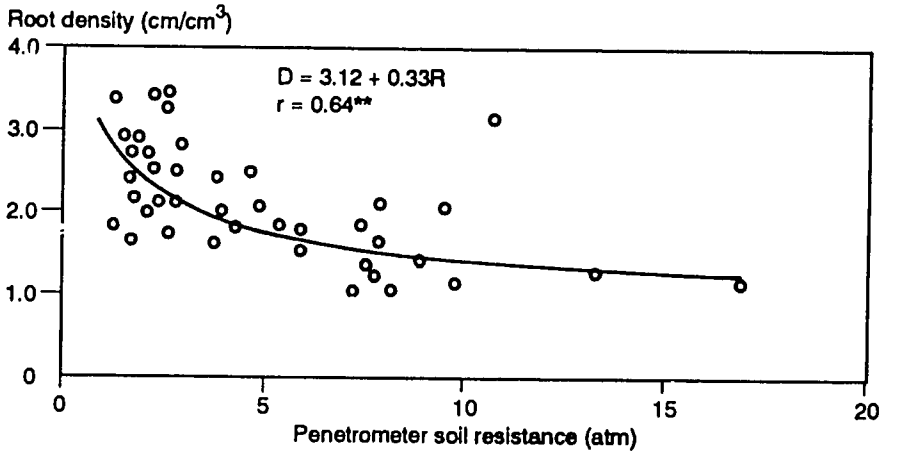


Figure 4. Wheat root growth related to the penetrometer soil resistance in an Oxisol. Source: M.J. Vieira, unpublished.

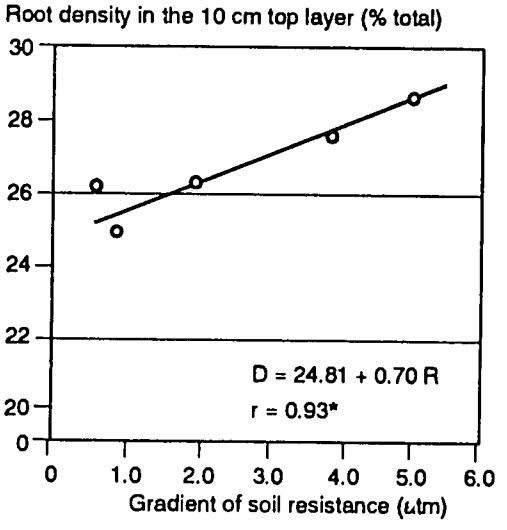


Figure 5. Wheat root density in the upper 10 cm in response to the soil resistance gradient between the plow pan and the disturbed top layer. Source: IAPAR.

conditions and found that these two factors are synergistic in their effect on root growth. In addition to the presence of aluminum, there usually is low availability of nutrients under these conditions.

Soil erosion

Erosion is the most visible result of soil and water degradation problems in the tropical areas of Latin America. Erosion is one of the most distinct symptoms of environmental degradation and one of the most important factors that reduces land quality.

Little data on soil losses caused by erosion on a large scale in Latin America are available. Measurements made in 1982 and 1983 by the State of Paraná on the Paraná River bed about 150 km above the Itaipu Dam showed an annual soil loss of

12.8 million tons. In experimental plots using traditional or conventional tillage systems for wheat-soybean double cropping, soil losses reached 10 to 20 t/ha per year. In addition to such aspects as lack of soil mulching, compaction, and tillage systems, rainfall patterns combined with long slopes (7-8%) and rolling landscapes have contributed to accelerated erosion in the wheat growing areas.

Relationships between Tillage Systems and Physical Degradation

The various soil tillage and continuous wheat-soybean double cropping systems have been important factors in the development of this soil degradation.

One of the main problems in wheat growing areas is the lack of mulch left on the soil especially after wheat harvest. In traditional and some conventional tillage systems, farmers burn the wheat straw after harvest for the following reasons:

- The straw chopper adapted to the combine harvesters requires additional power and leaves strips of straw on the ground that hinders tillage equipment.
- The straw decomposes too slowly for the soil to be prepared for sowing of the next crop.
- Tillage is usually done with soil moisture above the friability limit. As a consequence, wheat straw mixed with soil adheres to the edges of the disks and impedes penetration, especially for the heavy disk harrow.
- Herbicides do not work effectively if straw is present.
- Seeding machines (i.e., tyned soil opener) adapted to working through straw are scarce.

Wheat straw burning, in addition to the high decomposition rate of the soybean plant debris, leaves a low level of residue on the soil surface during part of the year. Besides straw burning, the traditional and conventional tillage systems result in limited cover on the surface due to intensive mixing of the arable layer. This contributes to the decrease of organic matter in the topsoil (Machado and Brum 1978, Cintra et al. 1983) and the increase of soil temperature and moisture loss (Vieira 1981b, Derpsch et al. 1984, Derpsch et al. 1986).

In addition to these aspects, the burning of crop residues dramatically increases surface splash erosion (Table 2), runoff, and soil erosion (Figure 6). Surface disaggregation through splash erosion makes the soil susceptible to surface sealing and a rapid decrease in infiltration rates (Roth et al. 1987).

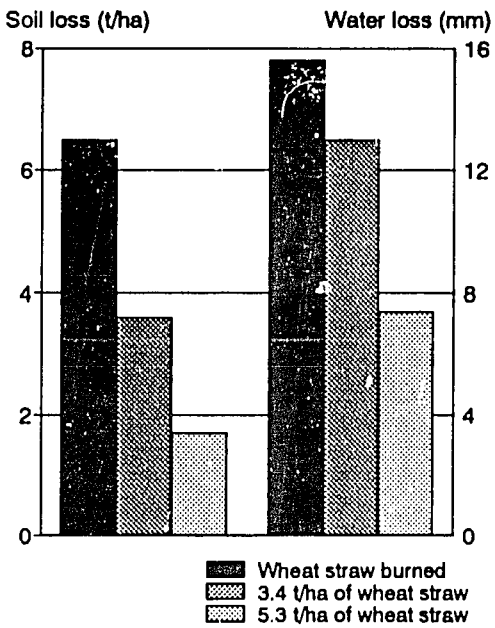


Figure 6. Soil erosion as affected by different management and amounts of wheat crop residues. Source: Vieira and Mondardo (1981).

Many farmers no longer burn straw because of the availability of tyned seeding machines and tillage equipment and more efficient post-emergence herbicides for use against weeds in the straw cover.

As far as soil surface pulverization and aggregate stability are concerned, the traditional and conventional tillage systems have been the most harmful (Sidiras et al. 1982, Vieira and Muzilli 1984). Figure 7 shows the soil aggregate stability behavior in three different tillage systems. As it can be seen, the conventional system shows lower aggregate stability compared to chiseling and no-tillage.

However, while it has been shown that the traditional and conventional tillage systems used in the wheat-soybean rotation promote soil compaction, no-tillage can also result in high levels of bulk density on the surface layer (Vieira and Muzilli 1984). This increase in bulk density values under no-tillage is a function of uncontrolled field traffic during the wet periods and no loosening of the arable soil layer.

Thus, soil tillage can be a major influence on soil erosion. When the tillage system employed results in lack of surface mulch,

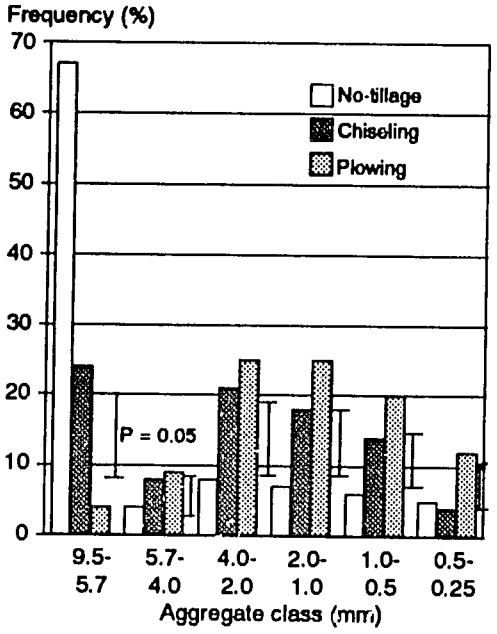


Figure 7. The distribution of soil aggregate classes in the topsoil (0-10 cm) resulting from different soil tillage methods in an Oxisol. Source: Sidiras et al. (1982).

Table 2. Effects of the rainfall intensity and soil surface conditions on splash erosion in different soil tillage systems.

Rain characteristics			Bare soil				Mulched soil			
Time (min)	Intensity (mm/h)	Energy (J/m².min)	CT	CP	NT	Mean	CT	CP	NT	Mean
			(g/m²)							
30	30	9.6	784	549	86	473a	717	248	22	309t
30	60	21.4	1374	775	149	766b	1243	577	104	641u
30	90	31.6	8464	3536	437	4146c	7986	1315	108	3137v
Mean			3541A	1620B	224C		3316T	713U	78V	
%			100%	46%	6%		100%	21%	2%	

CT = conventional tillage, CP = chisel plow, NT = no-tillage.
Numbers followed by the same letters do not differ significantly (DMRT, P = 0.05).
Source: Sidiras et al. (1982).

pulverization of the surface soil, and formation of a plow pan, erosion becomes severe. Figure 8 shows the sediment and nutrient flows in the Paraná River, which has a catchment area that includes a large part of the warm wheat cropping area. The sediment and nutrient transport increases during the two tillage periods, showing that soil erosion caused by running water and soil tillage are closely related. Several papers have shown this relationship for warm areas where wheat is grown in similar conditions (Vieira and Mondardo 1981, Castro et al. 1986, Bertol et al. 1987).

The effects of burning wheat straw and the number of light disk harrowings are shown in Figure 9. The combined effects of straw burning plus numerous harrowings increase soil erosion considerably. Unfortunately, this joint effect is particularly common in the wheat-soybean cropping system where traditional tillage is used. Nevertheless, erosion could be reduced in the traditional system if the wheat straw was incorporated into the soil instead of being burned (as in conventional tillage). Reducing the number of harrowings and properly using heavy disk harrows at the

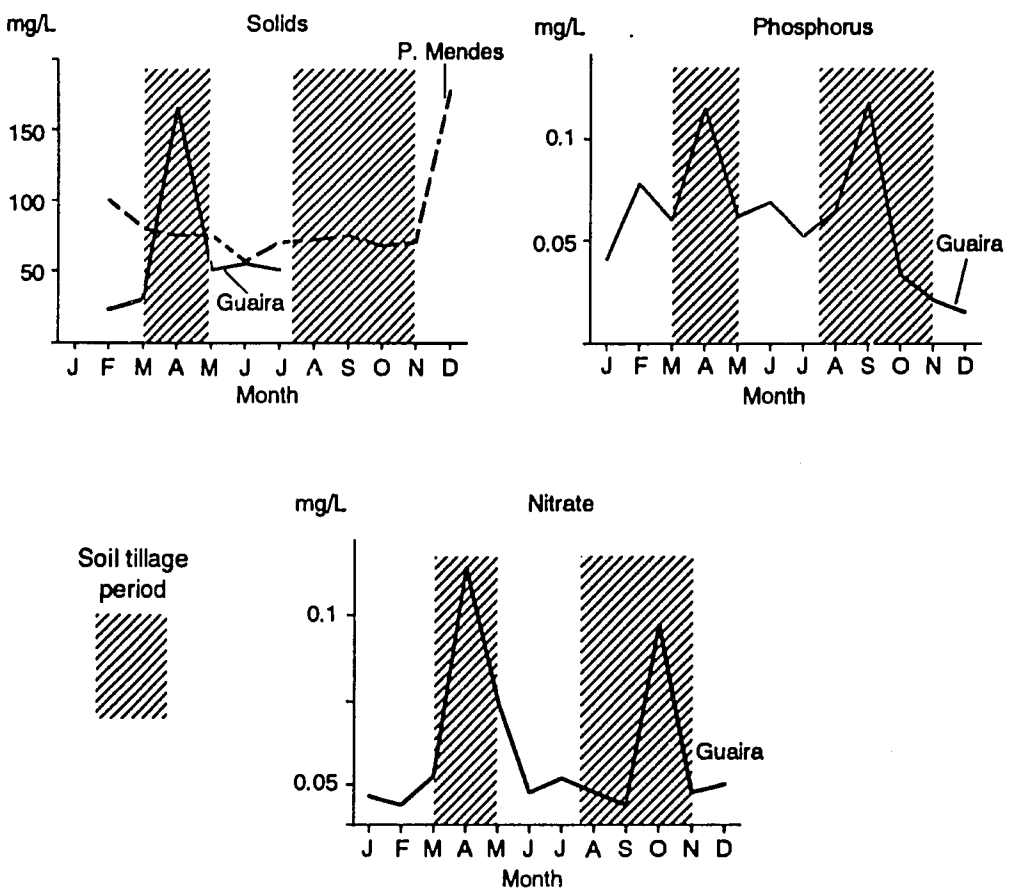


Figure 8. Nutrients and sediment flow in the Paraná River, sampled at P. Mendes and Guaira, 150 km upstream of the Itaipu Dam. Source: Surhema, unpublished, and Sorrenson and Montoya (1984).

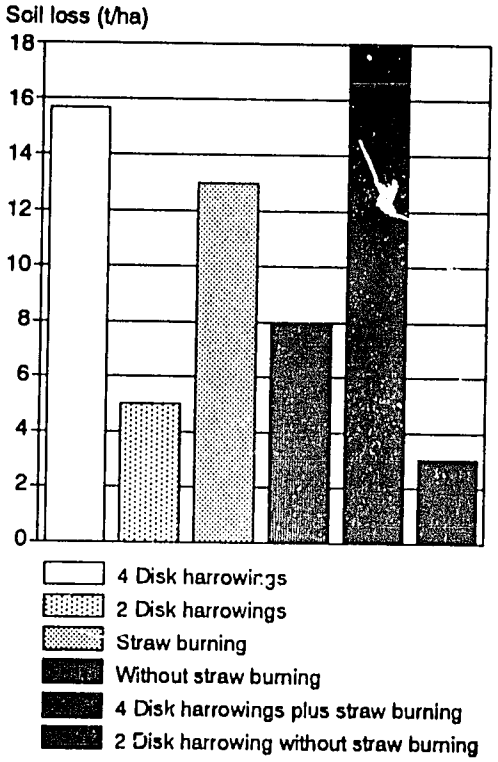


Figure 9. Soil losses as affected by wheat straw burning and number of light disk harrowings. Source: Vieira and Mondardo (1981).

correct soil moisture and traction speed could also improve the situation (Vieira and Mondardo 1981).

The chisel plow and no-tillage systems are most effective in reducing erosion. These systems increase the amount of crop residue remaining on the soil surface after tillage, maintain soil structure, mainly aggregate stability (Vieira and Muzilli 1984, Derpsch et al. 1984), reducing soil crusting and sealing which helps increase water infiltration (Roth et al. 1987), and reduces runoff (Lopes et al. 1987b).

Finally, Figure 10 shows the water infiltration rates under the three tillage systems. Infiltration rate under no-tillage is substantially greater than that using conventional tillage. With chisel plowing, water infiltration has intermediate values between the other two systems.

Crop and Tillage Systems Related to Wheat Productivity

Wheat crop productivity in the nontraditional warm areas depends on many factors and constraints. Some—such as soil fertility, soil tillage, and crop

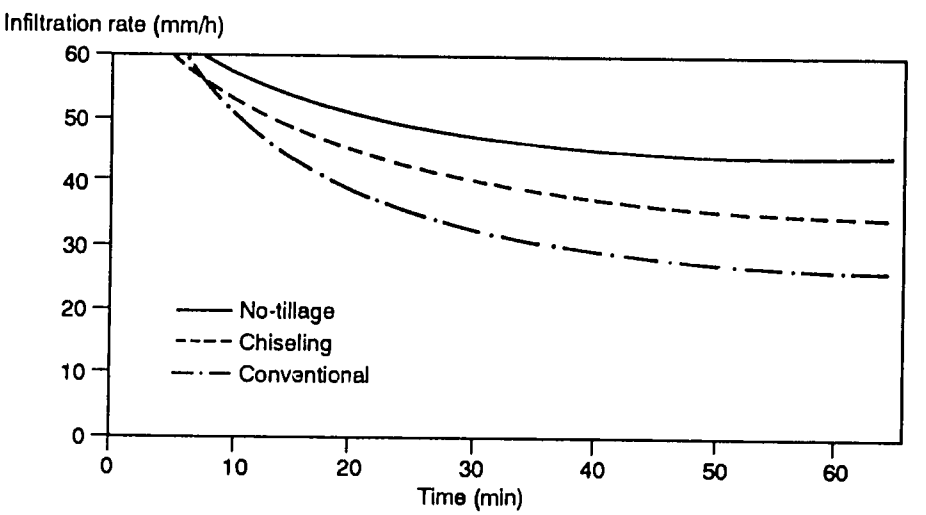


Figure 10. Infiltration rates in an Oxisol during the soybean cycle under different tillage systems at a rainfall intensity of 60 mm/h. Source: Derpsch et al. (1986).

management—can be manipulated by the farmers. However, others—such as drought, frost, and diseases—are random happenings of nature. Therefore, it is often difficult to obtain significant and consistent results showing the effects of cropping systems and various types of soil tillage.

Nevertheless, it can be concluded that wheat crop productivity has been increased by adoption of no-tillage under many conditions, especially where short drought periods occur during the crop cycle. Sorrenson and Montoya (1984), after a detailed review of all results from Paraná, Brazil, to that time, concluded that no-tillage increased wheat productivity about 8% on average, compared to conventional tillage and chisel plowing, which were similar.

Vieira (1981b) showed that wheat crop productivity with no-tillage was higher than with conventional tillage (with wheat residues incorporated, not burned) in the northern Paraná region. In the southern region of the state, it was often lower, although in the dryer winters, wheat crop productivity was always higher utilizing no-tillage than with conventional tillage. In these trials, conservation tillage treatments have frequently shown nitrogen deficiency at the beginning of the crop cycle, which may restrict potential productivity under chisel plowing or no-tillage.

A long-term trial carried out in an Oxisol soil at the Paraná State Agricultural Research Institute (IAPAR) showed similar wheat crop productivity between the traditional and conventional systems. Wheat straw was not burned in either treatment. Since erosion was only slightly higher with the traditional system, it may be that the traditional system is not too harmful when the system includes incorporation of crop residues, reduced number of light disk harrowings, and the proper use of heavy disk harrowing.

The introduction of other crops into the popular wheat-soybean sequence can also benefit wheat crop productivity. Recently, Gaudêncio et al. (1989) obtained higher wheat productivity when a green manure and/or maize were grown in rotation with this sequence.

These data have been confirmed in a long-term trial carried out at IAPAR, in which no-tillage increased wheat productivity compared to conventional tillage. In addition, treatments where maize was grown in summer rotation with soybeans increased wheat productivity compared to the traditional wheat-soybean continuous sequence. This crop rotation also increased the crop response to no-tillage.

Few data are available that compare erosion and crop productivity. In central Brazil, Dedecek (1987) observed that soybean productivity was reduced 16, 32, 47, and 67% when simulated erosion removed the top 2, 5, 10, and 20 cm of topsoil, respectively. In the same trial, he observed that liming and fertilizer did not restore crop productivity to levels of the noneroded treatment.

Approaches to Overcome Physical Soil Degradation

The following situations and factors should be considered:

- The tropical ecosystem is fragile where soil organic matter has an important role in the physical and chemical reactions taking place in the soil profile.
- Continuous wheat-soybean double cropping contributes little to adequate soil cover and crop residue since wheat

residues rarely exceed 4 t/ha and soybeans speed up residue decomposition.

- Soil tillage systems that do not have high mulching rates contribute to the decrease of soil structure quality, and also affect wheat growth, especially the root system, exposing the crop to greater risk of drought and nutrient stress.

- None of the tillage systems are 100% efficient in satisfying all the agricultural objectives over the long-term.

Based on the above points, the following guidelines can be suggested for the nontraditional, warm areas where wheat is grown.

- Introduce crop rotation systems that increase the amount of residues with a high C/N ratio, in spite of the crop requirement for more N.

- Adopt soil tillage systems that allow residues to stay totally or partially as surface mulch.

- Substitute heavy disk equipment with tyned or no-tillage systems.

- Practice flexibility in tillage systems and cropping patterns to overcome specific problems such as soil compaction, weed control, soil acidity, etc.

- Assess residue management using phytopathology studies.

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Resumen

Los oxisoles y ultisoles son los suelos predominantes en las zonas cálidas donde tradicionalmente no se cultiva el trigo en América Latina. Son suelos arcillosos donde los óxidos de caolinita, hierro y aluminio constituyen los minerales más importantes en la fracción arcillosa. En general es escasa la capacidad de intercambio catiónico y el contenido de materia orgánica es inferior al 3.5%. Cuando es elevada la humedad del suelo, estos tipos de suelo tienen una consistencia pegajosa y plástica. El sistema de producción agrícola más importante es el cultivo del trigo en invierno, seguido por la soya en el verano. También se siembran pequeñas extensiones con maíz y algodón como alternativa de la soya. Por lo menos cuatro sistemas de labranza del suelo son frecuentes en las zonas que se analizan: el tradicional, el convencional, el arado de cincel y la labranza cero; pueden existir además varias combinaciones de estos sistemas.

Como consecuencia de la fragilidad del ecosistema tropical, estos suelos pueden resultar degradados físicamente cuando se emplean sistemas inapropiados de labranza y manejo del suelo. Los problemas más comunes observados son la pulverización del estrato superficial, una capa dura por debajo de la capa arable y la erosión del suelo. Los sistemas de labranza que incluyen la quema de los residuos de los cultivos y el empleo de maquinaria con discos son en particular responsables de esos problemas. Los sistemas de labranza del suelo tienen diversos grados de eficiencia y la elección de uno específico, junto con la menor utilización de maquinaria y el mejoramiento de los sistemas de rotación de cultivos, parecen detener o, incluso, revertir el proceso de degradación física del suelo.

Tillage Practices and Soil Degradation in the Wheat Cropping Systems of the Warmer Areas of Africa and Asia

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Abstract

Soil degradation, due to physio-chemical and biological processes set in motion by anthropogenic factors, is a widespread problem in the warm wheat growing regions of Africa and Asia. Decline in structural conditions and reduction in quality and quantity of soil organic matter lead to crusting, compaction, low infiltration rate, high surface runoff, and accelerated soil erosion. The latter is a serious problem in ecologically sensitive regions in South Asia and East Africa. Some irrigated wheat-producing arid and semi-arid regions in South and West Asia are highly prone to salinization and alkalization. Soils intensively cultivated to the wheat-rice rotation in South Asia are particularly susceptible to salt imbalances in the root zone. The problem is further compounded by drought stress, high evaporative demand, and lack of plant-available water reserves in the root zone. Competition by weeds and other pests can also be a severe yield constraint.

A principal goal of soil surface management is to alleviate these constraints, improve wheat production, and enhance soil quality. When available, using crop residue mulches and other organic wastes improve water storage in the root zone. Fallowing is another widely recommended practice for water conservation. The problem of soil compaction can be minimized through management of vehicular traffic. Guided traffic that reduces the number of passes of heavy machinery and zonal tillage such as ridge-or chisel-tillage are relevant practices toward a judicious management of soil compaction. There is no universal system for sustainable management of soil and water resources. Appropriate options differ among soils, cropping systems, and biophysical and socio-economic environments. Most practices are site-specific and have to be validated under local conditions.

Introduction

Soil degradation refers to decreased agricultural productivity due to reduction in the quality of the soil's life-support processes (Lal 1989a). It includes physical, chemical, and biological deterioration such as decline in soil structure, depletion of soil fertility due to leaching or nutrient imbalance, reduction in quantity and quality of soil organic matter, and decline in population and species diversity of soil biota.

A principal process of soil degradation, set in motion by a decline in structural conditions, is soil erosion. Soil erosion is a severe problem in some wheat growing regions of warmer areas of Africa and Asia, e.g. Morocco, Tunisia, India, Pakistan, and the East African Highlands. It is estimated that as much as 1 billion tons of topsoil are lost from the Ethiopian Highlands each year (Brown 1981). The Simen Mountains of Ethiopia are severely eroded (Hurni 1983). Estimates of sediment load from the Yellow River of China indicate that the average loss of topsoil throughout the watershed is about 26.9 t/ha (Robinson 1981). Average erosion rates in some rivers of northern India are estimated to

be 25.3 t/ha (Narayna et al. 1985). Erosion rates in Nepal are as high as 157 t/ha (Hurni 1985). Consequences of soil erosion in terms of loss in productivity, pollution of water, and damage to reservoirs and waterways can be enormous.

Declines in structural condition and the reduction in quality and quantity of soil organic matter are responsible for widespread problems of crusting and formation of surface seals, compaction and hard-setting. Formation of crusts and surface seals inhibit seedling emergence and cause poor stands. Soil compaction leads to poor root system development and renders wheat susceptible to drought stress and lodging. Structurally inert soils in seasonally warm regions with intense summers are particularly vulnerable to this form of physical degradation. Physical and biological degradation are inter-dependent. Intensive cultivation with reduced or no-input can lead to drastic reductions in soil organic matter content, decline in biomass carbon, and reduction in activity of soil biota. The latter is also adversely affected by indiscriminate use of agri-chemicals. In contrast, agronomic techniques based on liberal use of crop residue mulch, fallowing and cover crops, and no-till or reduced tillage systems help build up soil organic matter content (Lal 1989b).

Excessive build-up of salts in the root zone, due to salinization or alkalization, is another problem in arid and semi-arid wheat producing regions of Asia. The climatic factors responsible for salt imbalance include those that reduce or eliminate leaching. Some irrigated wheat-producing areas of India, Pakistan, China, and the Middle East are highly prone to developing salinity problems (Gupta and Abrol 1990).

Drought stress—the lack of plant-available water reserves in the root zone—coupled with a high evaporative demand of the atmosphere is another soil-related constraint to wheat production in Asia and Africa. Drought stress is caused by soils of low water holding capacity and by a high climatic aridity. The latter is characterized by low and erratic precipitation, high evapo-transpiration, high temperatures, and low humidity. High soil temperatures are also associated with high radiation and low soil-water reserves. The problem of drought stress is further accentuated by competition from weeds. Reduction in wheat yield due to weed competition can be as much as 31% (Moody 1974). Regehr et al. (1990) observed in Morocco that detrimental effects of weeds are most pronounced when wheat is also suffering from other stresses such as drought and Hessian fly damage.

Alleviating Soil-Related Constraints

Soil erosion on sloping lands is caused when rainfall rate exceeds the infiltration capacity. Furthermore, structurally weak soils slake rapidly due to raindrop impact and inundation, and detached soil particles are readily transported in surface runoff. In structurally inert soils, characterized by low organic matter content and containing predominantly low-activity clays, tillage systems that enhance surface detention capacity and reduce runoff are effective in reducing the risk of soil erosion. Surface detention capacity can be increased by a rough and cloddy seedbed. Another system is the tied-ridge method of seedbed preparation. The tied-ridge system comprises a ridge-furrow system on the contour with cross-ties in between. In Israel Morin et al. (1984) reported that a system of tied-ridges or basin tillage effectively eliminated over 90% of the runoff and over 70% of the erosion (Table 1). The basin tillage can decrease runoff by at least 50% as compared with the conventional planting system. Even in

relatively dry years, the basin tillage with 1.6-m wide beds was effective in increasing wheat yields by about 50%.

Soil erosion on structurally-active soils can be minimized by improving its infiltration capacity. Infiltration capacity is influenced by volume, size, continuity, and stability of macropores. Structurally-active soils are characterized by high soil organic matter content and contain predominantly high-activity clays. If already compacted, their porosity can be improved by soil loosening through inversion, chiseling or by para-plow. Once loosened, a high infiltration rate can be maintained through reduced or no-till systems, mulch farming, and other conservation tillage systems.

Soil erosion can also be curtailed by strip cropping, contour plowing, and installation of vegetative hedges on the contour. Grass hedges, maintained on the contour at suitable intervals, are very effective in reducing runoff rate and velocity and causing sediment deposition. In soils with high stone concentrations, stone-lines established on the contour are also effective in reducing risks of soil erosion. Vegetative hedges or stone-lines facilitate formation of natural terraces over a period of time.

Water conservation

Increasing the water storage capacity of the root zone is a major objective in dryland farming. Water conservation is achieved by increasing infiltration, decreasing runoff, reducing evaporation, and minimizing uptake by weeds. Most soil conservation systems described above are also effective in water conservation. In addition, crop residue mulches are effective in minimizing crusting and formation of surface seals, improving infiltration capacity, and decreasing losses due to evaporation. Crop residue mulches, if available at 4-6 t/ha, can be extremely effective in conserving soil-water. In hilly regions of northern India, Sharma and Acharya (1987) reported significant improvements in wheat grain yield due to mulching (Table 2). In addition to water conservation, mulching also improved plant uptake of N and P. A major constraint in mulch farming is the unavailability of mulch. Because crop

Table 1. Tillage effects on runoff, erosion, and wheat yield in arid regions of Israel.

Treatment	Runoff (mm)	Erosion (kg/ha)	Wheat yield (kg/ha)
Control, sown on flat	17	293	975
Fallow plots	21.9	397	—
Tied-ridges, 1.6 m-wide plots	7.9	156	1403
Tied-ridges, 0.6 m-wide plots	7.4	72	964

Total seasonal rainfall = 98.6 mm.
Source: Morin et al. (1984).

Table 2. Effects of tillage methods on wheat yield in hilly regions of northern India.

Treatment	Grain yield (kg/ha) 1980-81	1981-82
Zero cultivation	2575	1950
Conventional cultivation	2700	2300
Conventional cultivation + mulch	3460	3450
Deep plowing	3050	3225
Inter-row cultivation	2285	1925
LSD (.10)	333	395

Source: Sharma and Acharya (1987).

residues are precious and used as fodder in Asia and Africa, their availability for mulching is questionable.

Fallowing is another widely recommended practice for water conservation. This practice involves growing a crop in alternate years so that water is conserved during the crop-free period for use by the subsequent crop. Repeated tillage is performed to created the so-called "soil mulch" or "dust mulch". Amir et al. (1990) reported that a fallow cropping system at Gilat, Israel, resulted in 104 to 220% more grain yield in years with below-average rainfall, but had no significant effect in years with above-average rainfall. The effectiveness of this practice also depends on success in weed control. Weed control during fallowing can be achieved by tillage. Delay in weed control can significantly reduce soil-water content at the time of wheat planting in a wheat-fallow system (Lavake and Wiese 1979). Lack of summer tillage or delay of tillage can reduce yield of wheat by 40 to 50% (Yesilsoy 1990). In addition to tillage, weeds can also be controlled by herbicides. Herbicides are, however, expensive and not economically or readily available to resource-poor farmers of Africa and Asia. Furthermore, farmers use weeds as forage and deliberately delay harvesting them at the cost of less water conserved in the root zone.

Fallowing is not always effective and has several disadvantages. It is unjustified in regions of severe land shortage. Fallowing, with repeated cultivation for weed control, can also enhance risks of soil erosion. Planted-fallows, that is wheat grown in rotation with forages as leys or grain legumes, may be economically and ecologically better alternatives. In Iraq, Al-Fakhry (1990) observed that the yield of wheat grown after forages was significantly more than that after fallowing (Table 3). In seasons with below-average rainfall, wheat yield was more when grown after lentils and chickpeas that after fallowing. In India, Sharma et al. (1988) reported that yields of wheat grown in plots green manured with sesbania and crotolaria was more than that following pearl millet. Experiments conducted in northern Tanzania showed that wheat yields after leys, both with and without applied nitrogen, tended to be superior to those on continuously cropped land (Anderson et al. 1966). Frequent use of legumes or grass leys, therefore, is a soil enhancing practice with positive effects on the yield of wheat.

Managing soil compaction

Soils of warm climates with intense summers are easily compacted. The trampling effect of uncontrolled grazing can be responsible for the widespread problem of soil compaction. Once a soil is compacted, it is difficult to restore favorable structural conditions. The energy required to alleviate deep-soil compaction can be high. Compaction management is, therefore, an important objective in cropping systems.

One strategy is to avoid soil compaction through management of vehicular traffic. Minimizing the number of passes of heavy

Table 3. Effects of fallowing and rotation with forage mixtures and grain legumes on wheat yield in Iraq.

	Grain yield (kg/ha)	
Wheat after	First cycle (498 mm rainfall)	Second cycle (298 mm rainfall)
Fallow	1710	915
Forage mixture	2655	1015
Lentils	2125	1575
Chickpeas	1915	960

Source: Al-Fakhry (1990).

machinery is an important step. Guided traffic is a further option. In structurally-active soils, reduced or no-tillage systems may be workable solutions. In semi-arid regions of northern Nigeria, Maurya (1986) reported that, for a sandy loam soil, no-till maintained a higher level of soil organic matter, a higher basic infiltration rate, and a higher soil porosity than tilled plots. Over 2 years, equivalent yields of wheat were obtained in no-till without any input in seedbed preparation (Table 4). In shallow, weakly structured soils of South Africa, it has been observed that soil managed by a no-till system had more organic carbon than that cultivated using chisel or moldboard plows (Table 5). High levels of soil organic matter reduced soil strength and improved soil tilth. Soil strength was negatively correlated with soil organic carbon content:

$$y = 43.1 - 11.0x, \; r = -0.59^*$$

where y is soil strength in kPa and x is organic carbon content in percent.

A no-till system is, however, not effective in all soils and crops. Sandy soils are easily compacted and wheat yields can be

Table 4. Wheat grain yield as affected by crop residue management in northern Nigeria.

Treatments	Residue	Grain yield (t/ha) 1984	1985
No-till	With	4.35	3.50
	Without	4.15	2.95
	Mean	4.25	3.22
Plowed	With	4.35	3.80
	Without	3.60	3.75
	Mean	3.98	3.78
LSD (.05)			
	Tillage	NS	0.28
	Residue	0.20	NS
	Irrigation	NS	NS

Source: Maurya (1986).

Table 5. Tillage effects on properties of a shallow, weakly structured soil in South Africa measured in wheat 8 years after initiating the experiment (1985).

Treatment	Organic carbon (%)	Total N (ppm)
Moldboard plow	1.07b	590
Chisel plow	1.33ab	800
No-till	1.41a	800
LSD (.05)	0.31	NS

Source: Agenba and Maree (1989).

dramatically reduced with no-till in compacted soils. Furthermore, the usefulness of no-till in soil and water conservation depends on the availability of crop residue mulch. In Punjab, India, Bhatnagar et al. (1983) observed that a no-till system produced the lowest yield of wheat in sandy or sandy loam soils (Table 6), although tillage did not cause significant changes in soil physical properties. Incorporation of crop residues within the soil surface increased organic carbon and soil nitrogen.

There is no one tillage system that can be universally recommended for all soils and crops. The choice of an appropriate tillage system depends on the current soil condition and the cropping system being employed. There is a need to develop a soil-guide to recommend appropriate tillage methods for alleviating soil-related constraints to wheat production.

Managing salt-affected soils

Salt-affected soils occupy extensive areas in wheat growing regions of South and West Asia. Reclamation of these soils requires the removal of part or most of the salt and/or its replacement by more favorable cations, e.g. replacement of Na^+ by Ca^{2+}. Tillage plays an important role in

this process. Appropriate tillage is needed to improve drainage so that salts can be leached out of the root zone. Tillage is also needed for incorporation of organic materials in soils that would help increase infiltration rate and subsoil permeability. Growing wheat in rotation with rice is an important reclamation practice. Detailed reclamation procedures for salt-affected soils are described by Gupta and Abrol (1990).

Soil Surface Management for Sustainable Production

General objectives of tillage and soil surface management are outlined in Table 7. Short-term objectives include optimizing the seedbed environment, improving water conservation, controlling soil erosion, and managing soil compaction and salt imbalances. Long-term objectives are to preserve and sustain the soil's productive capacity. Appropriate methods of seedbed preparation to achieve these objectives differ among soils, cropping systems, and biophysical and socio-economic environments. Most practices are site-specific and have to be validated and adapted under local conditions. While no-till may be useful in one environment, deep tillage may be advantageous in another. Weed-free fallow is useful in seasons of below-average rainfall, whereas legume-wheat rotations are more productive in other conditions. Residue mulch left on the surface is useful in some environments and its incorporation judicious in others. It is important to realize that there is no panacea for all soils and environmental constraints.

Although specific cultural practices cannot be generalized in terms of their application, basic principles of soil and water management are applicable under wide range of ecological conditions. Some of these principles are summarized in Table 8. These are general guidelines that can be useful for developing technological options for soil surface management.

Table 6. Tillage effects on yield of wheat on coarse-textured soils of Punjab, India.

Treatment	Wheat yield (t/ha)		
		Sandy loam soil	
	Sandy soil	N_{80}[a]	N_{120}[a]
No-till	1.74	3.86	4.27
Disk plowing followed by harrowing	1.75	4.36	4.72
Disk plowing followed by harrowing + 5 t/ha of residue incorporated	2.58	4.71	5.03
Disk plowing followed by harrowing + 5 t/ha of residue mulch	2.12	4.44	4.63
Disk plowing followed by harrowing + 2.5 t/ha of residue incorporated and 2.5 t/ha applied as mulch	2.23	4.56	4.83
LSD (.05)	0.244	0.198	0.190

[a] N_{80} and N_{120} refer to nitrogen application rates of 80 and 120 kg N/ha, respectively.
Source: Bhatnagar et al. (1983).

Table 7. General objectives of soil surface management.

I. Optimize seedbed environment
- Proper seed-soil contact
- Reduce crusting and surface seal
- Optimum soil moisture, aeration, and temperature
- Minimum competition with pests

II. Improve water conservation
- Increase infiltration rate
- Enhance surface detention capacity
- Reduce runoff
- Decrease evaporation
- Improve root growth and development

III. Control soil erosion
- Decrease runoff volume and velocity
- Enhance soil structure
- Manage runoff for safe disposal
- Increase sediment deposition in buffer strips

IV. Manage soil compaction
- Reduce vehicle traffic
- Improve porosity
- Decrease soil strength

V. Decrease salt accumulation
- Improve leaching
- Enhance soil structure
- Incorporate organic matter and chemical amendments

Table 8. Possible techniques for decreasing runoff volume and peak runoff rate.

Soil	Principle	Technique
Structurally unstable coarse-textured soils.	Prevent surface scaling and raindrop impact.	Mulching, reduced tillage, cover crop.
Soils with low activity clays and coarse texture, in semiarid to arid regions.	Increase surface detention.	Rough cloddy surface, tied-ridge system, ridge-furrow system.
Loamy to clayey-textured soils easily compacted.	Improve infiltration.	Vertical mulching, chiseling, residue incorporation.
Good-structured soils. Soils with well-aggregated, stable structure.	Enhance porosity.	Residue mulching, no-till system, conservation tillage.
Vertisols; soils with expanding clay minerals in arid regions with short rainy season.	Maintain soil surface at moisture potential above the hygroscopic coefficient and reduce heat of wetting.	Mulching, soil inversion just prior to rain, fallowing, legume-wheat rotations.
Vertisols; soils with expanding clay minerals in semiarid or subhumid regions with long rainy season.	Dispose water safely and recycle for supplementary irrigation.	Graded ridge and furrow system with grass waterways and storage tank, camber bed technique.

In conclusion, the basic ingredients for improving and maintaining high wheat production can be summarized as:

- Liberal use of crop residue and other organic amendments.
- High frequency of forages and grain legumes in rotation with wheat.
- Use of judicious tillage depending on specific soil-related constraints.
- Reduction in number of passages of heavy machinery on the soil surface.
- Management of surface runoff for improving soil-water storage and decreasing erosion.
- Judicious use of off-farm input to enhance yields and profit.

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Resumen

La degradación del suelo provocada por procesos fisioquímicos y biológicos iniciados por factores antropogénicos es un problema muy difundido en las regiones cálidas de cultivo del trigo de Africa y Asia. El deterioro de las condiciones estructurales y la reducción de la calidad y la cantidad de la materia orgánica del suelo llevan al encostramiento, el apisonamiento, una tasa baja de infiltración, el escurrimiento superficial elevado y la erosión acelerada del suelo. Esta última es un problema grave en las regiones del sur de Asia y el este de Africa, sensibles desde el punto de vista ecológico. Algunas regiones semiáridas y áridas del sur y el oeste de Asia donde se produce trigo bajo riego son muy propensas a la salinización y la alcalinización. Los suelos intensamente cultivados con la rotación trigo-arroz en el sur de Asia son particularmente sensibles a los desequilibrios salinos en la zona de la raíz. El problema se complica por la sequía, la elevada demanda evaporativa y la falta de reservas de agua disponibles para las plantas en la zona de la raíz. La competencia de la maleza y otras plagas también puede constituir una severa restricción del rendimiento.

Una de las principales metas del manejo de la superficie del suelo es disminuir estas restricciones, mejorar la producción de trigo y aumentar la calidad del suelo. Cuando es posible, el empleo de mantillos de rastrojo y otros desechos orgánicos mejora el almacenamiento de agua en la zona de la raíz. El barbecho es otra práctica muy recomendada para conservar el agua. El problema del apisonamiento del suelo se puede reducir al mínimo mediante el manejo del tránsito vehicular. El tránsito guiado para reducir el número de pases con maquinaria pesada y la labranza zonal, como la labranza con arado de cincel o con surcos, son prácticas útiles para evitar el apisonamiento del suelo. No existe un sistema universal para el manejo sostenible de los recursos del suelo y el agua. Las opciones apropiadas difieren según los tipos de suelo, los sistemas de cultivo y los ambientes biofísicos y socioeconómicos. La mayoría de las prácticas son específicas para cada sitio y deben ser verificadas en las condiciones locales.

The Effects of Tillage Practices and Crop Rotation on the Epidemiology of Some Major Wheat Diseases

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Abstract

In nontraditional, warmer areas, instability in wheat productivity is due to constraints such as drought stress, soil acidity, and low fertility. Inappropriate management practices such as no crop rotation can also hinder wheat production in that they have a direct influence on the severity of some major diseases. Foliar disease severity, especially of tan spot, is increased due to the over-summering of the pathogen in wheat residues. Because of changes in cultivation practices, this disease has become increasingly important in several tropical and subtropical regions of the world, where earlier it was not important or else was not reported. Root rot diseases like common root rot, rhizoctonia, sclerotium, and take-all are also more severe in no tillage than in the conventional cultivation systems. Normally, the severity of such diseases is dependent on the amount of rainfall during the early part of the crop cycle. In most cases, crop rotation is extremely important in restricting such diseases to low levels. Where changes in crop rotation are not possible, deep tillage systems should offer a potential compromise, like plowing once a year after the soybean crop or once in 2 or 3 years, depending upon the disease and its severity. Nevertheless, in general, an integrated disease management approach is most desirable.

Introduction

The tropical and subtropical regions of the world are known for their unstable agricultural production and fragile ecosystems. Increased deterioration of the soil structure is due to heavy mechanization, which leads to soil compaction and erosion, reduction in the water infiltration rate, and loss of organic matter. The instability in wheat production and productivity in these regions is due to several major constraints:

- Unpredictable climatic conditions, primarily lack of water.
- Soil acidity and low fertility.
- Improper management practices, including no crop rotation, which can have a direct influence on the severity of some diseases.

In this paper, attempts are made to analyze the effects of the last constraint on the epidemiology of some major foliar and root diseases.

Common Tillage Systems Used in Warmer Areas

The tillage systems used in these areas can be classified into three categories:

- Traditional system, which includes burning wheat straw after harvest followed by one heavy disk harrowing and two to five light harrowings before soybean seeding. There is heavy traffic on the soil, which causes soil compaction between the 10- to 15-cm depth and finally results in severe soil erosion. In addition, organic matter is destroyed and water infiltration is drastically decreased (Muzilli 1985).

- Conventional system, where only one plowing is used followed by two light harrowings.

- No-tillage system (direct drilling), where no plows or harrows are used and the wheat is sown directly by using special sowing equipment.

The conventional and no-tillage systems are superior because their use can reduce soil erosion losses by up to 90% compared to the traditional system (Muzilli 1985). No tillage has an additional advantage over the conventional system because it increases surface mulching, which consequently increases the soil's water holding capacity.

No tillage was adopted by some farmers in Paraná State (Brazil) in the early 1970s and by 1975, the area under this system for the soybean-wheat rotation was estimated to be about 50,000 ha. During the 15 years since, the area has steadily increased until in 1990 it was estimated to be more than 350,000 ha (20% of Paraná's total wheat area). In Paraguay the area under no tillage is also gradually increasing.

Effects of No Tillage and Crop Rotation on the Epidemiology of Some Major Diseases

Foliar diseases

Substantial information is available in the literature regarding the effects of no tillage and crop rotation on the epidemiology of crop diseases. However, only those that are related to the major disease problems of tropical and subtropical areas will be discussed here.

Wheat is attacked by several diseases, however, spot blotch, leaf rust, stem rust, Xanthomonas streak, and tan spot are considered to be the major foliar diseases for the warmer, nontraditional wheat areas. Powdery mildew may sometimes be important as well.

Tillage practices and crop rotation influence the survival mechanism of some foliar disease pathogens. The influence of tillage on foliar diseases may also be through alteration of crop vigor and the micro-environment within the crop (Rees 1987).

According to Rees (1987), the higher severity of powdery mildew and leaf rust in tilled land appears to be associated with reduced mineralization of nitrogen in untilled soil leading to less vigorous and, hence, less susceptible growth as well as a less favorable micro-environment within the crop.

Rust pathogens do not survive on crop residues. Our results indicate that the Xanthomonas streak pathogen (*Xanthomonas campestris* pv. *undulosa*) is seed-transmitted and does not oversummer in wheat residue possibly because of the high summer temperatures of 30-38°C between November and February (unpublished data). Hence, tillage practices and crop rotation do not influence the survival mechanism of these disease pathogens.

Spot blotch—Although the spot blotch fungus—*Cochliobolus sativus* Ito et Kurib *Helminthosporium sativum* P.K. and B. (Syn. *Bipolaris sorokiniana* Sacc. et Sorokin)—survives on some crop residues including wheat, so far, there is no indication nor any report in the literature about the influence of tillage practices on the severity of this disease. The perfect state of this pathogen is not reported to occur in warmer, nontraditional wheat areas. It is believed that the high temperatures during summer may inactivate or even kill a substantial

amount of the inoculum present on the stubble in no tillage cultivation. The fungus attacks and survives on several grass species and the conidia are carried by wind for long distances, and thus the role of stubble inoculum on the epidemiology of the disease is not great. The spot blotch fungus is also seed-transmitted.

Septoria diseases—The severity of septoria nodorum blotch, caused by *Leptosphaeria nodorum* (Muller) and septoria tritici blotch caused by *Mycosphaerella graminicola* (Fuckel) Schroeter, could be affected by tillage practices and crop rotation since these two pathogens survive on the crop residue (Rees 1987). However, they will not be dealt with here because they are of little or no importance for most of the tropical and subtropical areas.

Tan spot—In contrast, the severity of tan spot is affected by tillage practices in almost all the wheat growing areas of the world. Tan spot of wheat, caused by *Pyrenophora tritici repentis* (Died.), *Drechs.* (syn. *Drechslera tritici repentis* (Died.) Shum.) occurs worldwide. Severe tan spot epidemics have been reported in Australia, Brazil, Nepal, Kenya, USA, and Canada (Hosford 1982). According to Hosford (1982), the disease can cause yield losses of nearly 40%. In Australia, Rees et. al (1982) reported a loss in grain yield of about 49%. In Paraná, we recently estimated 36% yield losses attributed to tan spot (unpublished data). Rees and Platz (1979, 1980, 1983), Rees et al. (1982), and Rees (1987) have studied the epidemiology of tan spot in detail under Australian conditions. Summer et al. (1981) presented a good review on the effects of tillage practices on the epidemiology of some diseases.

In Brazil, da Costa Neto (1968) observed tan spot for the first time on cereals and grasses in the state of Rio Grande do Sul. Later, severe tan spot incidence was reported at the Ponta Grossa experimental station in southern Paraná (Mehta 1975). However, it was not found occurring in commercial wheat fields until 1979. After 1979, tan spot severity increased gradually in the states of Paraná and São Paulo; during the last 4 years it has become as important as spot blotch. As in Australia and the USA (Lamy 1982, Rees and Platz 1979), the gradual increase of the disease's severity during the past few years has been linked to the expansion of no tillage wheat cultivation in Brazil and Paraguay. The tan spot pathogen survives easily on the almost undisturbed wheat stubble.

In the northeastern wheat areas of Australia until 1970, tan spot was not considered a major disease. However, in the 1970s, the trend to retain wheat stubble rather than burning for soil conservation purposes caused tan spot to become a significant disease in this region (Rees and Platz 1979).

In a permanent experiment installed in 1976 at the Paraná Agronomic Institute Foundation (IAPAR), Londrina, to compare no tillage with the conventional tillage system, periodic observations were made in both systems from 1982 to 1985, regarding tan spot severity and the survival mechanism of the pathogen. Although there was no winter crop rotation, there was a definite sequence of crops as follows:

- Soybean-wheat-soybean-wheat (A).
- Maize-wheat-maize-wheat (B).
- Cotton-wheat-cotton-wheat (C).

- Soybean-wheat-maize-wheat (D).
- Cotton-wheat-maize-wheat (E).
- Soybean-wheat-cotton-wheat (F).
- Maize-wheat-soybean-wheat-cotton-wheat (G).

Each treatment (sequence of crops) had three replications in each cultivation system. The experimental design was randomized blocks and with an individual plot size of 200 m^2 (25 x 8 m). Percentage of leaf area (top three leaves) infected was recorded by visual observation (0-99%), on 8-10 random plants per plot. The average disease severity was used to express the percentage of leaf area infected per plot.

Figures 1, 2, and 3 show the average percentage of leaf area infected at the soft dough stage for each treatment and each system. There were no differences in

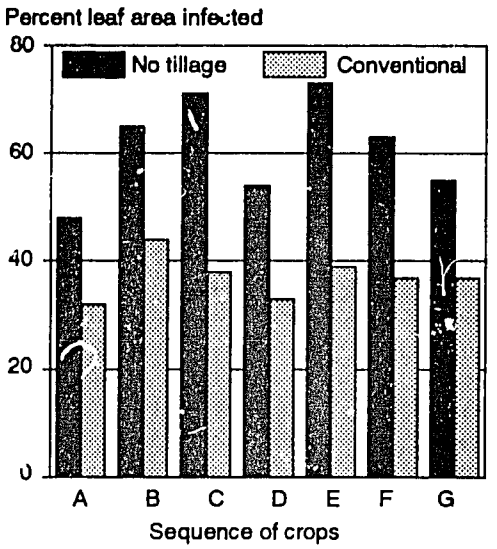

Figure 2. Effect of tillage practices on the severity of tan spot in wheat cultivar Mitacoré. Disease assessment was done 92 days after sowing. Londrina, 1983.

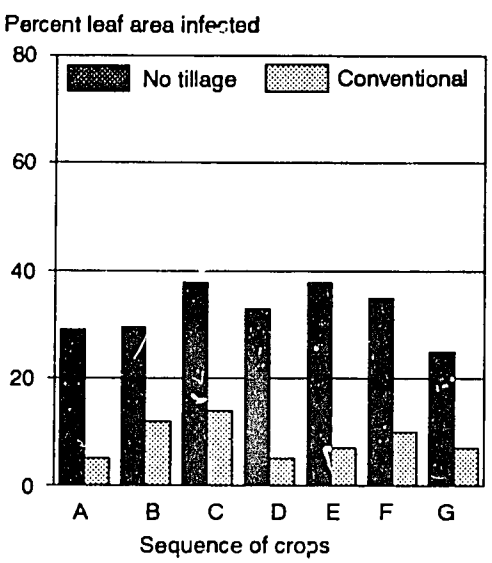

Figure 1. Effect of tillage practices on the severity of tan spot in wheat cultivar Mitacoré. Disease assessment was done 73 days after sowing. Londrina, 1982.

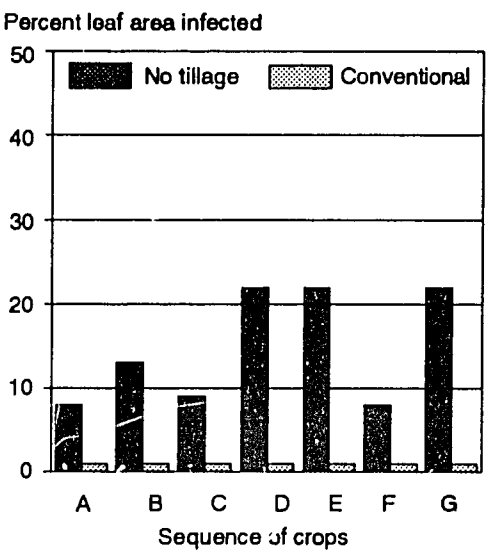

Figure 3. Effect of tillage practices on the severity of tan spot in wheat cultivar Mitacoré. Disease assessment was done 96 days after sowing. Londrina, 1984.

disease severity between the cropping sequences. However, irrespective of the cropping sequence, tan spot severity during 3 consecutive years was always substantially higher in the no tillage system. Table 1 shows the date of seeding and rainfall during the crop cycle over the 3 years. The disease intensity in 1984 was much lower (Figure 3) compared to 1982 and 1983 (Figures 1 and 2) due to a prolonged drought during the early part (June and July) of the crop cycle. During these months, the average rainfall was only 3.3 and 3.0 mm, respectively. 1983 was very favorable for the disease since average rainfall in May and June was high, 308.0 and 260.5 mm, respectively. In 1982, the tan spot severity was higher because the experiment was seeded on May 30 and the rainfall in June was 259 mm. Thus, it is evident that disease severity is conditioned by the amount of rainfall between germination and the end of tillering.

Primary infection comes from ascospores. The first tan spot lesions were usually observed within 25 to 30 days after sowing in the plots with no tillage, while in the conventional cultivation system the first symptoms were observed 15 to 20 days later.

Normally, tan spot severity is higher in no tillage because of better plant development in the no-till crop, which results in a higher plant density and consequently a more favorable microclimate—and also because in no tillage, the disease starts much earlier than in the conventional tillage system.

Perithecia are normally present throughout the year on the wheat stubble. During 1983-85, samples of wheat stubble from the no tillage and conventional systems were periodically examined for the presence or absence of perithecia. Table 2 shows that the perithecia were almost always present in the no-till plots, whereas they were present in the conventional plots for only a short period between harvest and land preparation for soybean planting.

Several glasshouse and field experiments conducted during 1982-1987 indicated that tan spot is not seed-transmitted—at least under our conditions.

Hosford (1982) and Krupinsky (1982) have reported several cereal and grass species to be hosts of *P. tritici repentis*. Since more than 33 hosts of *P. tritici repentis* are reported, we did not do any artificial inoculation studies to determine the host range. However, under our conditions, we examined the commonly occurring cereal and grass species to determine the pathogen's survival mechanism. Tan spot was observed occurring naturally on wheat and triticale, rarely on oats, and not at all on

Table 1. Amount of rainfall and the critical months responsible for tan spot severity during 1982-84, Londrina, Paraná, Brazil.

Year/date of wheat seeding	Total rainfall (mm) per month				
	April	May	June	July	August
1982 Seeded on May 30	26	59	259	155[a]	37
1983 Seeded on May 17	103	309	281[a]	17	0
1984 Seeded on May 21	213	65	3	3[a]	70

[a] Amount of rain in critical months for tan spot severity.

Digitaria horizontallis, *Digitaria insularis*, *Brachiaria plantaginea*, *Cencrus echinotus*, *Eleusine indica*, *Panicum repens*, *Paspalum maritimum*, *Sorghum halepense*, and *Secalis ceralis*. Rees (1987) reported that crops other than wheat and some triticale cultivars are resistant to tan spot.

There is no evidence of long distance dispersal of ascospores. According to Rees (1982), few ascospores travel distances of more than 100 to 300 m (Table 3).

These studies indicate that the tan spot fungus survives and over-summers primarily on wheat stubble in the no-till system, which provides the inoculum source for the succeeding wheat crop. Later, the conidia produced on the primary lesions on wheat are carried for considerable distances by wind and infect neighboring wheat fields planted conventionally. Consequently, the secondary cycle of the conidial production in both systems further disseminates the disease to other wheat fields. Hence, the ascogenus state of the fungus is the most important state in the disease's epidemiology. Rees (1982) and Lamey (1982) also reached similar conclusions in Australia. The over-summering of the pathogen during the prolonged hot periods in Latin America and northeastern Australia, and at the same time its over-wintering in North Dakota and Nebraska, demonstrate the wide range of temperatures under which the pathogen can survive.

It is, therefore, obvious that wheat stubble in no-tillage cultivation must be eliminated to break the disease cycle and consequently control the disease. Soil mulching is necessary at least for the tropical and semitropical areas, mainly to increase the soil's water holding capacity for control erosion. The only choices left are: 1) burning of the wheat stubble, 2) crop rotation, 3) plowing soon after the soybean harvest, 4) breeding for resistance, and 5) chemical control.

Burning wheat stubble helps reduce the initial inoculum, but does not eliminate the pathogen completely. Rees (1982) reported that stubble burning greatly influenced the level of tan spot on the primary leaves (Table 4), however, a relatively small amount of infected stubble can result in a considerable amount of disease under favorable conditions. Thus, stubble burning is not

Table 2. Occurrence of perithecia of *Pyrenophora tritici repentis* on the wheat stubble in no-tillage and conventional tillage systems of cultivation during 1983-85.

Months of observation	Amount of perithecia present[a]	
	Conventional	No-tillage
October 1983	*	***
December 1983	*	***
January 1984	*	**
March to June 1984	0	*
August 1984	0	0
September 1984	0	*
October-November 1984	*	**
January to May 1985	0	***

[a] 0 = Perithecia absent; * = Very few perithecia; ** = Many perithecia; *** = Abundant perithecia.

Table 3. Gradients of tan spot from infected stubble with *P. tritici repentis* in Queensland, Australia.

Site	Lesions/leaf at distance (m) from stubble							
	0	10	20	40	60	100	200	300
A	126	11.3	9.6	6.0	4.5	3.3	1.7	1.3
B	33.3	12.9	9.4	7.6	4.7	3.9	-	-
C	26.2	13.0	9.5	3.8	3.3	3.2	-	-

Source: Rees (1982).

recommended; in addition to not being highly effective, it would also induce soil erosion.

Tan spot can be managed at low levels through crop rotation (Lamey 1982). There are some options for crop rotation practices and the choice of a particular crop depends on whether it is used for grain production, green manuring, or fodder and whether there are regional commercial problems and Government incentives (Table 5). Oats seem to be a good option. Sunflower and maize have problems with frost and disease. For smaller areas, peas (*Pisum sativus*) and chickpea (*Cicer arietinum*) can be grown successfully (A.C.P. Motta, IAPAR, pers. comm.).

Bearing in mind the data of Rees (1982), it would appear that considerable infection can occur with only small amounts of inoculum remaining on the surface stubble. Vertical tillage systems (i.e., conservation tillage) are generally designed to retain as much crop residue on the surface as possible. Thus, it would appear that these tillage systems are unlikely to give appreciable cultural control of tan spot. However, local data are needed on the relationship between residue retention and crop infection. In the absence of crop rotation, it is possible that continuous no-tillage agriculture may lead to tan spot infections in wheat that reduce the economic viability of the system. In these conditions, rotation or soil tillage must be practiced periodically. Although plowing in a no tillage system aimed at destroying wheat stubble completely disturbs the soil structure and the cultivation system per se, a compromise in the vertical tillage system is needed. Plowing, on the other hand, incorporates the stubble and breaks up soil compaction. If the soil is to be plowed to incorporate stubble once a year, it seems—for conditions of the Southern Cone of South America—that it would be best to do it after soybean harvest and then seed the wheat into tilled soil. In this way, stubble is retained during the rainy season when erosion is a substantial threat and it is incorporated before the wheat crop to control tan spot. In Pergamino, Argentina, wheat yields are higher with this combined tillage scheme than with either continuous no tillage or continuous conventional cultivation (Fernando et al. 1987).

Tan spot can be further reduced through breeding for resistance. Although a slow process, this approach should be given considerable attention. Hosford (1982) has published comprehensive information about the developing knowledge of

Table 4. Effect of stubble management and tillage on tan spot levels in Australia.

Treatment		Surface stubble	Lesions/leaf	
Stubble	Tillage	(g/m²)	Primary leaf	Flag leaf
Retained	Zero	152.9 A	11.75 A	51.3 A
Retained	Conventional	32.2 B	2.43 B	33.3 B
Burnt	Zero	19.9 C	0.83 C	27.7 C
Burnt	Conventional	8.7 C	0.62 C	26.5 C

Values in each column followed by the same letter do not differ ($p<0.05$).
Source: Rees and Platz (1979).

breeding for tan spot resistance. Currently, breeding for resistance is being done in USA and Australia (Frohberg 1982, Rees and Platz 1990) where some sources of resistance have been identified. However, more resistance sources are needed.

Chemical control, a last resort measure, can be used in absence of other control measures or as a complement to other methods. Chemical control of tan spot in no-tillage cultivation is more difficult because of the constant release of

Table 5. Options of winter crops for crop rotation practices in Brazil.

Winter crop	Purpose	Commercial situation
Wheat	Grain production	±2% imported
Barley	Grain production	Imported
Lupins	Incorporated in soil	300,000 ha grown
Vicia sativa	Incorporated in soil	Cultivation insignificant (lack of seed)
Rye	Grain production	Depends on Government subsidy
Oats	Grain production	
Maize	Grain production or incorporation (after early soybean variety in Paraná seeded 2nd week of October)	At times imported
Sunflower	Grain production (after early soybean variety)	
Linseed	Grain production	75 t imported (100-200,000 ha grown)
Rapeseed	Grain production	12 t imported (100-500,000 ha grown)
Pigeon peas	Incorporated in soil	
Mucuna	Incorporated in soil	
Green peas	Grain production	Imported
Chick peas	Grain production	Imported
Crotalaria spp.	Incorporated in soil	

Source: CNPTrigo, Passo Fundo.

ascospores from the stubble. Hence, there are different approaches for the two systems.

With no tillage, fungicidal spraying should be done as a preventive measure during the initial stage of crop development, i.e., 35-40 days after sowing. The number of applications depends on the weather conditions; however, experience in Brazil shows that, under environmental conditions favorable for epidemic development, two applications at a 15-day interval are usually sufficient. Effective fungicides against tan spot are dithiocarbamate- and triazol-based. With conventional cultivation where the disease epidemics normally start somewhat later, the first chemical application should be given after the initial appearance of disease symptoms.

Root Diseases

Although wheat root systems are attacked by a relatively small number of soilborne fungal pathogens, especially in the nontraditional, warmer areas, several can cause severe damage and appreciable yield losses. These include *Helminthosporium*, *Fusarium*, *Rhizoctonia*, *Sclerotium*, and *Graeumannomyces* spp. Their importance is influenced by several factors, including tillage practices and crop rotation.

Common root rot

While common root rot of wheat is a disease complex that includes both *Helminthosporium* and *Fusarium* species, the major pathogen involved in the syndrome is *Cochliobolus sativus*. The disease has been reported in all the wheat growing areas of Brazil (Diehl et al. 1983a,b; Diehl and Sonego 1983), causing yield losses of about 20% (Diehl et al. 1982). It is also reported from all areas where wheat or barley is grown in Canada; according to Conner et al. (1987), the root rot damage goes unnoticed because above-ground symptoms are not always evident. Yield losses of 5.7% per year have been reported in spring wheat on the Canadian prairies (Ledingham et al. 1973). According to Duczek (1989), early root rot infection lowers a plant's yield potential by reducing the number of tillers. It also causes seedling death and thereby reducing plant stand.

In Paraná, the influence of crop rotation and tillage practices on root rot severity has been studied in two different permanent experiments. IAPAR has been conducting the first experiment continuously at Londrina since 1976 and at Castro (southern Paraná) between 1980-1983 to compare the effects of no tillage and conventional cultivation on crop yields. Details of this experiment were described earlier.

The National Research Center for Soybeans (CNPSoja/EMBRAPA) is conducting the second experiment at Warta to study the effect of crop rotation practices within no tillage systems on the yields of wheat and soybeans. The experiment is divided into three parts: Part I initiated in 1984, Part II in 1985, and Part III in 1986—all three have similar plot sizes (562 m^2) and treatments and have four replications. Eight different crop rotations include:

- Wheat-soybean-wheat-soybean.
- Oats-soybean-wheat-soybean.
- Lupins-maize-oats-soybean-wheat-soybean-wheat-soybean.
- Lupins-maize-wheat-soybean-wheat-soybean-wheat-soybean-wheat-soybean.
- Lupins-maize-wheat-soybean.
- Oats-soybean-oats-soybean-oats-soybean-wheat-soybean.

- Lupines-maize-oats-soybean-oats-soybean-wheat-soybean.
- Lupins-maize-oats-soybean-wheat-soybean.

For root rot ratings, 100 plants are uprooted carefully at about 30-day intervals from the two central rows of each plot. The plants are washed thoroughly and individually scored for root rot intensity using the system described by Diehl et al. (1982).

Effects of tillage practices were studied at Londrina and Castro during 1980-1982. Material at Londrina was completely lost in 1981 due to prolonged drought. Figures 4 and 5 show that root rot at Londrina and Castro develops gradually during the wheat growing season, but the disease intensity in both years was slightly higher with no tillage. There were no apparent differences among the eight crop sequences. The disease progress curve was faster in 1980 than in 1982 (Figures 4 and 5), probably due to below average rainfall early in the crop cycle at both locations in 1980 (Table 6). Although final disease intensity was always very high at both locations during 1980 and 1982, it seems that the rate of disease progress was reduced drastically in rainy 1982—suggesting that common root rot may become severe in arid and semi-arid tropical regions where rainfall may be low between sowing and the end of tillering.

In the second experiment at Warta (CNPSoja), attempts were made to verify the effects of crop rotation in no tillage cultivation on root rot severity. Disease intensity increased gradually during the crop cycle. Since there were no statistically significant differences within the experiments regarding the disease and yield, data for the three parts of the experiment are not presented separately. Although oats were incorporated into the soil as a green manure, on average, root

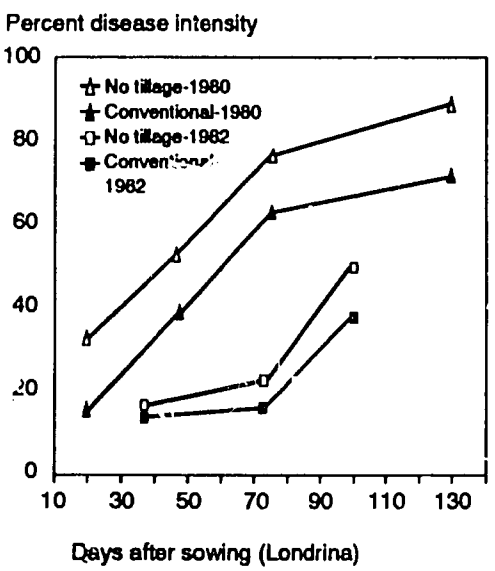

Figure 4. Effect of tillage practices on the intensity of common root rot of wheat during 1980-82, Londrina, PR., Brazil.

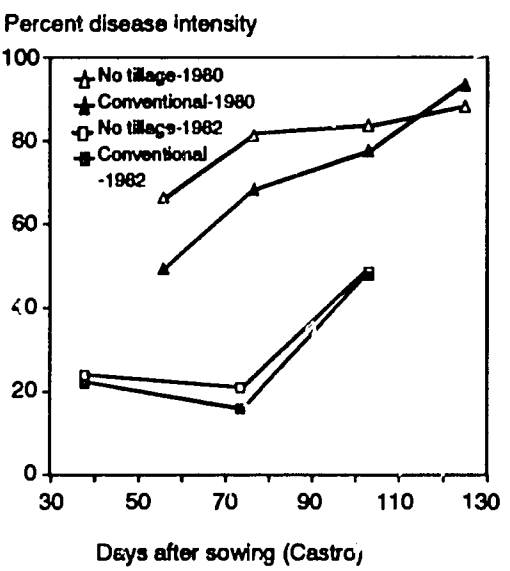

Figure 5. Effect of tillage practices on the intensity of common root rot of wheat during 1980-82, Castro, PR., Brazil.

rot was significantly less severe in oats than in wheat during the 4-year study—indicating that oats are a good option within the rotation sequence. Reis and Baier (1983) obtained similar results.

The effects of crop rotation on root rot severity, considering the average of the three parts of the experiment over the 4-four year period (1986-1989), were studied. In crop rotation treatments where wheat was grown every 2-3 years, the average root rot intensity was slightly lower than the other rotations where wheat was grown every year or in alternate years. However, such differences were not statistically significant. The experiment is only 4 years old and possibly it may take a few more years for the crop rotations to clearly demonstrate their effects in reducing the disease's severity. The nonsignificant differences could also be, in part, due to the level of varietal susceptibility, since every year a different variety has been used in the Warta experiment.

Considering the average root rot intensity of all rotation treatments, it seems that intensity increased with time, especially in Part I, since it was installed earlier than Parts II and III. Disease intensity almost doubled during the 4-year period (Figure 6), indicating that build-up of the pathogen population in the soil is a rather slow process and may take some years before causing acute damage. However, the higher disease intensity in 1989 was, in part, due to drought at the beginning of the crop cycle. Similarly, in 1988 disease intensity was lower than in 1987 principally because 1988 was a wet year (183.9 mm in April, 246.7 mm in May, and 59.6 mm in June). Once again, this indicates that rainfall at the beginning of the crop cycle determines the severity of damage. At Warta, the experiments were always seeded in April.

The relationship between the disease and yield was studied using averages of the four replications per treatment in each part of the experiment over the 4 years. The correlation between yield and the disease was negative and highly

Table 6. Amount of rainfall and the critical months responsible for common root rot severity during 1980-82 at Londrina and Castro, Paraná, Brazil.

Location/year/date of wheat seeding	Total rainfall (mm) per month				
	April	May	June	July	August
Londrina, 1980					
Seeded April 15	115	118	65 [a]	92	93
Londrina, 1982					
Seeded May 30	26	59	260 [a]	155	37
Castro, 1980					
Seeded June 13	131	55	84 [a]	202	94
Castro, 1982					
Seeded June 30	48	82	306	152 [a]	87

[a] Amount of rain in critical months responsible for root rot severity.

significant (Figure 7). The analysis indicates that for every 1% increase in root rot intensity, there was a yield loss of 46 kg/ha. The relatively low correlation coefficient (-0.49) was due perhaps to some differences in varietal susceptibility, effects of crop rotations, and also the effects of variable rainfall during early crop growth over the period.

Our results indicate that common root rot may become a severe problem in semi-arid tropical regions. However, Diehl et al. (1982) and Diehl and Sonego (1983) reported that the disease may also be very severe in moist, semi-tropical regions.

Duczek (1981) reported that in Canada *C. sativus* spores were far more numerous in tilled soil than in undisturbed soil layers. Similarly, Reis and Abrao (1983) reported that the propagules of *C. sativus* in soil

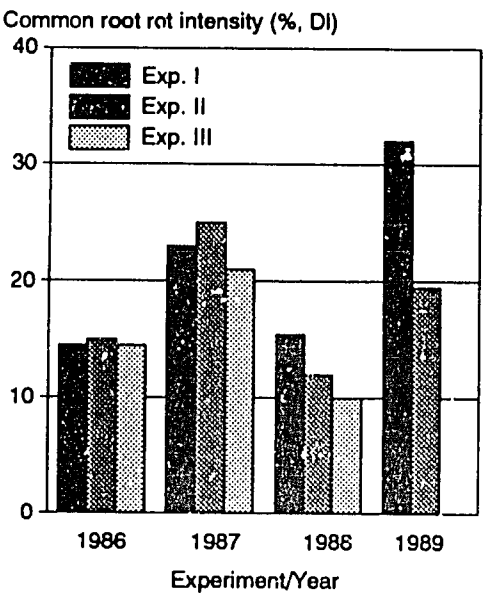

Figure 6. Progress of common root rot of wheat in no tillage during 1986-89 at Warta, PR., Brazil.

were significantly more numerous in plots where wheat following soybeans was seeded conventionally than where no tillage was practiced in Rio Grande do Sul.

Diehl (1979) reported a decrease in root rot severity in wheat grown on land left fallow for 3 or 4 years. Later, Diehl et al. (1982) studied disease incidence and intensity in 17 fields in Rio Grande do Sul and concluded that much less disease developed in fields that were fallow for 3-4 years or not previously cropped to wheat than in those cropped annually or after 1 or 2 years of fallow. They also found that the inoculum quantity of *C. sativus* present after 1 or 2 years of fallow was significantly lower than the fields seeded to wheat every year.

Is the severity of common root rot dependent only on the amount of propagules in the soil? More data must be generated to answer this question, especially for the semi-arid tropical areas. However, according to the data presented here it seems that the amount of rainfall during early crop growth has a significant influence on root rot severity. It is known that shallow seeding also influences the severity of the disease (Greaney 1946, Broscious and Frank 1986).

Take-all

Take-all disease of wheat, caused by *Gaeumannomyces graminis* (Sacc.) Oliver & Von Arx Var. *tritici*, is basically a disease of cooler and humid areas. The fungus attacks the root system and is characterized by the presence of white heads that are either scattered or in circular patches in the field. Yield losses are quite variable, but can be up to 100% in some fields—especially in southern Paraná and Rio Grande do Sul. In these regions, the severity of take-all depends on the degree of soil acidity, high aluminum content, and the amount and manner in which lime is applied.

Reis et al. (1983) reported that, in Rio Grande do Sul in wet years, the severity of root rot (mainly take-all), was much higher in monocropping than in 1 or 2 years of winter rotations without wheat, and that yield decreases were proportional to the increases in disease severity. Disease intensity is drastically reduced when wheat is grown after lupins (Reeves et al. 1984, Rovira 1990). Cook (1981) also reported that take-all was mild or nonexistent on wheat grown after oats, potatoes, or alfalfa. Besides crop rotations, tillage practices also have an influence on-take-all severity. Moore and Cook (1984) reported that seeding wheat in a no-tillage system resulted in more take-all than where the soil was tilled.

In their extensive survey of root diseases of wheat in Brazil, Diehl et al (1983b) and Diehl and Sonego (1983) did not observe any take-all in Mato Grosso do Sul or northern Paraná, but found some in western Paraná and a lot in southern Paraná. After studying take-all under the Brazilian system of agriculture, Rovira (1981) concluded that the average difference of 5°C in ambient air temperature between southern and northern Paraná is responsible for the absence of the disease in the north. Higher temperatures in the north apparently enhance biological control of take-all because the fungus may not survive if the soil temperature exceeds 27°C for 7-10 hours each day from November to March.

Thus, it is evident that take-all may not be a problem in the semi-arid and warmer tropical regions, even if no tillage cultivation system is widely adopted.

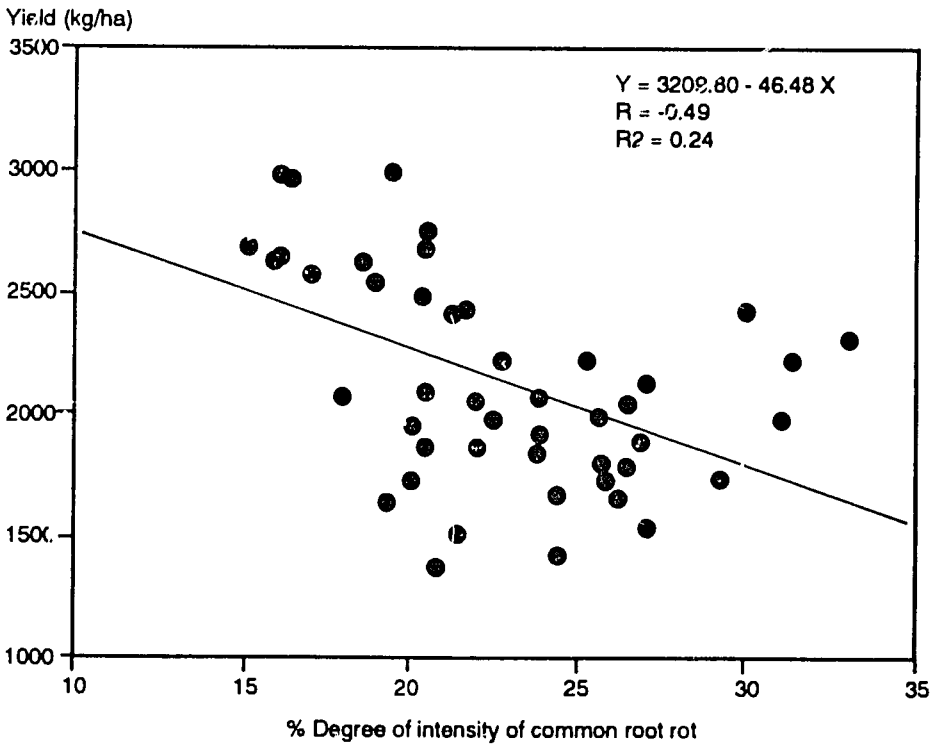

Figure 7. Relationship between the intensity of common root rot of wheat and the yield after 4 years of cropping in no tillage. Warta, PR., Brazil.

Rhizoctonia root rot

Rhizoctonia root rot, also known as "bare patch", is caused by *Rhizoctonia solani* Kuhn (syn. *Thanatephorus cucumeris* (Frank) Donk). It was reported as a pathogen of cereals over 60 years ago in Australia (Roget et al. 1987). In recent years, it has been reported on wheat in Brazil (Mehta and de Nazareno 1983), the USA (Weller and Cook 1986) and countries in South and Southeast Asia (Hobbs et al. 1988). There are several strains of *R. solani* that cause either root rot or sharp eyespot (Weller and Cook 1986) and they have a very wide host range.

Although the disease is not yet a serious problem in nontraditional, warmer areas, these is concern especially in view of the changing cultural practices and gradual expansion of no tillage cultivation. According to Rovira (1986, 1990) and Weller and Cook (1986), the disease is more common in cereals grown under conservation or no tillage systems than in cultivated soils.

In Paraná, the disease occurs sporadically and at low intensities, and its differential severity in no tillage is yet to be detected. No information about the effect of crop rotation on the disease is yet available.

Sclerotium

Sclerotium root rot is caused by *Sclerotium rolfsii* Sac. The fungus is soilborne and attacks many plant species. Yield losses in wheat can be up to 30% (Hobbs et al. 1988). It has been reported on wheat in Brazil (igarashi et al. 1983, Mehta and de Nazareno 1983), Ecuador, Peru, Bolivia, and many countries of Southeast Asia (Dubin 1985). Punja (1988) has published a good account of the disease.

In Brazil, sclerotium was first reported to occur in Paraná in 1980 and 1981. The disease is more severe during wet years than dry years. Although the disease was observed in patches in several fields in northern Paraná in 1980 and 1981, so far there is no evidence of its expansion to other areas or even within the same fields it was first discovered.

Since the disease is favored by high temperatures and moisture, it is supposed to be more severe in no tillage than conventional systems. Deep plowing of infested fields prior to planting has been shown to reduce inoculum levels, compared with disking provided residual inoculum levels are sufficiently low (Punja 1988). However, according to Punja (1988), plowing was most effective when used in combination with other control measures. Therefore, with no tillage some modifications are necessary, such as deep plowing every 2 to 3 years, especially in the infested areas. Nonetheless, deep plowing may be impractical for relatively small holdings as is the case in most of Southeast Asia (Hobbs et al. 1988). Control of this disease seems to be more problematic for the warm and humid tropics.

Since the pathogen has a very wide host range, crop rotation will have little or no effect in reducing the soil inoculum. Satisfactory disease control in this case can only be obtained through an integrated approach which might include, deep plowing, crop rotation with a less susceptible host, application of higher doses of nitrogen and calcium, and varietal resistance (Punja 1988).

Conclusions

It could be said that the intensity of tan spot and some root diseases can be affected either by the cultivation system or by crop rotation practices. More

information is needed in this respect for the semi-arid and warmer tropical regions. No tillage cultivation is expanding rapidly and is responsible for the increase in tan spot severity in no-tilled as well as conventionally-tilled wheat. Crop rotation practices would help in reducing the severity of most of the foliar and root diseases; however, its applicability is somewhat restricted. It is a challenge for plant pathologists, agronomists, and agricultural engineers to develop appropriate modifications to tillage and cultural practices to minimize the pathogen inoculum that oversummers on the soil surface without substantially reducing the advantages of no tillage. Modifications in tillage and cultural practices, on the other hand, may also be impractical, especially for regions with small-scale farmers. Alternative integrated disease management systems should then be investigated for such situations.

Acknowledgments

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Resumen

En las zonas cálidas donde tradicionalmente no se produce el trigo, la inestabilidad de la productividad del cereal obedece a restricciones tales como la sequía, la acidez del suelo y su escasa fertilidad. Las prácticas inapropiadas de manejo también pueden obstaculizar la producción del cereal, como, por ejemplo, el no practicar la rotación de cultivos, que puede influir directamente en la severidad de algunas enfermedades importantes del trigo. La severidad de las enfermedades foliares, en especial la de la mancha bronceada, aumenta porque el agente patógeno sobrevive al verano en los residuos de trigo. A causa de la modificación de las prácticas de cultivo, esta enfermedad se ha vuelto cada vez más importante en varias regiones tropicales y subtropicales del mundo, donde antes no tenía trascendencia o no había sido observada. Las enfermedades que afectan la raíz, como la pudrición común de la raíz, la pudrición por Rhizoctonia, *la marchitez de los cereales y el mal del pie, también son más graves con la labranza cero que con los sistemas tradicionales de cultivo. Normalmente, la severidad de esas enfermedades depende de la cantidad de precipitación pluvial a comienzos del ciclo de cultivo. En la mayoría de los casos, la rotación de cultivos es en extremo importante para reducir los niveles de esas enfermedades. Cuando no es posible introducir cambios en la rotación de cultivos, ofrecerán una posible solución los sistemas de labranza profunda, como la práctica de arar una vez al año después de cosechar la soya o una vez cada dos o tres años, según la enfermedad y su severidad. Sin embargo, en general lo más conveniente es un método integrado de control de enfermedades.*

Do Crop Rotation and Green Manuring Have a Place in the Wheat Farming Systems of the Warmer Areas?

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Abstract

The effects of crop rotation and green manuring on cash crops are analyzed on the basis of double cropping wheat production systems in Brazil. This experience should have useful elements for research and development of crop rotations in other parts of the world. After testing and studying different green manure crops, it was found that Avena strigosa *Schieb.,* Raphanus sativus *L. Var.* Oleiferus *Metzg., and* Lupinus albus *L. are among the most promising green manure crops for the region studied. The effect of different green manure crops in reducing weed infestation, their influence on water infiltration and soil conservation, the residual effect of green manure crops on cash crops, and the economics of green manure crops are presented. It is also shown that adequate crop rotations result in better use of available machinery and labor, lead to reduced disease and weed infestations and N fertilizer requirements, and contribute to higher yields. Economic analysis shows that higher annual gross margins can be obtained with integrated crop rotations that include green manure crops and no-tillage practices compared to traditional production systems.*

Introduction

Crop rotation is defined as a regular and orderly change in the cultivation of different crops, in a time sequence, on a given location (Geisler 1980). Monoculture of annual crops, on the other hand, is defined as repeating the same crop each year on the same location. In the tropics and subtropics, some of so-called crop rotations are closer to the definition of a monoculture, despite the fact that two crops are cultivated each year. This is also reflected in international literature where many publications can be found on 1-year crop sequences (double cropping), but much less work has been carried out on 2 or more years of wheat crop rotations in warmer areas. An exception to this seems to be southern Brazil where crop rotation is an important topic of research especially during the last decade.

Wheat farming systems of the warmer areas are extremely diverse due to the wide range of ecologic conditions (climate, soil, topography), which have an influence on weed flora, diseases, pests, mechanization, etc., and also due to contrasting socioeconomic conditions, different farm sizes, production costs, markets, etc. Therefore, it will not be possible to discuss here the many wheat farming systems practiced in the warmer areas. Some of the typical production systems that could be mentioned are: soybean-wheat, rice-wheat, maize-wheat, cotton-wheat, and potato-wheat.

Due to market conditions and to the ideal combination of a leguminous crop with a cereal, double cropping of soybeans and wheat has become a widely used system in Brazil, Argentina, and Paraguay. From a total wheat production area of approximately 9 million hectares in these countries, an estimated 5.8 million hectares were double-cropped to soybeans and wheat in 1990 (M.M. Kohli, pers. comm.). In other countries like the United States and Japan, double cropping wheat and soybeans is a well established system.

Because of the importance of this crop sequence in several countries and its potential on extensive areas of mechanized agriculture, this paper will concentrate on this farming system. Instead of drawing on worldwide experiences with wheat-based crop rotations for the warmer areas, this paper draws on research results from Paraná and southern Brazil, where consistent and more homogeneous information is available. The Brazil experience will hopefully answer the question: do crop rotation and green manuring have a place in the wheat farming systems of warmer areas? This experience should also have useful elements for research and development of crop rotations in other parts of the world.

For a better understanding of double cropping soybeans and wheat in Brazil, note that soybeans are generally planted in the warmer summer season (October-March) and wheat is planted in the colder winter season (April-September). Table 1 summarizes climatic conditions of Londrina, Paraná, from where many research results are presented in this paper.

Alternative Green Manure Crops

Green manuring is an essential component in alleviating soil fatigue, conserving the soil, and achieving sustainable crop production. Therefore, green manure crops should always be included in crop rotations that aim for sustainable yields.

To know which green manure crops are best adapted to the soil and climatic conditions of a certain location, researchers must test all potential species for the different agroecologic regions and understand their main characteristics, such as speed of growth and soil cover, resistance to diseases and pests, influence on weeds, green and dry matter production, N content, C/N ratio, etc. Table 2 presents the most promising green manure crops and their characteristics for the Londrina, Paraná location. Black oats (*Avena strigosa* Schieb.) and oil seed radish (*Raphanus sativus* L. Var. Oleiferus Metzg. obtain the highest dry matter production. With 147 and 135 kg N/ha respectively, more total N was found in the plants and roots of these crops than in leguminous crops such as lupins (*Lupinus albus* L.), where 90 kg/ha were measured. Even if nonleguminous green manure crops do not produce N, they can contribute by bringing reasonable amounts of N to the soil surface that would otherwise be lost by leaching.

Table 1. Climatic conditions at Londrina, Paraná, Brazil, 23°23'S, 51°11'W, 556 masl (Mean 1953-1980).

Rainfall (mm)	
Annual mean	1615
Mean summer crops (Oct.-March)	1090
Mean winter crops (April-Sept.)	525
Mean wettest month (January)	227
Mean driest month (August)	58
Maximum rainfall in 24 hours	250
Temperature (°C)	
Annual mean	20.7
Mean hottest month (January)	23.9
Mean coldest month (June)	16.6
Absolute maximum (February)	37.5
Absolute minimum (July)	-3.5
Relative humidity (%)	
Annual mean	73.0
Sunshine	
Hours per year	2560

Source: IAPAR, Características Climáticas de Londrina, 1982.

When C/N ratios of the different green manure crops were analyzed, variations in the top growth between 15 and 42 were observed (Table 2). Research in Paraná has shown that, after green manure crops with a C/N ratio of <23 (i.e., lupins, oil seed radish), main crops—preferably cash crops with a high N demand (i.e., maize)—should be sown as quickly as possible to reduce N losses. On the other hand, when leguminous cash crops are sown, green manure crops with a high C/N ratio (>25 i.e., black oats, rye) should be used, otherwise symbiotic N fixation by these crops would be negatively affected due to excessive nitrates in the soil during the early growth stage (Heinzmann 1985).

Influence of Green Manure Crops on Weed Infestations Compared to That of Wheat-Fallow

Green manure crops and their residues can have a major influence in reducing weed infestations. Almeida and Rodrigues (1985) have shown that there is a linear correlation between the amount of biomass produced by cover crops and the effectiveness in suppressing weeds (Figure 1). They also showed that different cover crops have a marked influence on the specific composition of

Table 2. Characteristics of some green manure species in Paraná, after a vegetative period of 139 days (125 days for sunflowers), planted on April 12, 1982. Crops were planted without fertilizer (except wheat and rapeseed: 30 kg N/ha).

Species	Dry matter of aerial part		Root mass dry matter (0-90 cm)	Total N			C/N Ratio
	kg/ha	%	kg/ha	Aerial kg/ha	Roots kg/ha	Sum kg/ha	Aerial/Root
White lupins "bitter" (*Lupinus albus* L.)	2710	18.0	1500	57	33	90	23/20
Hairy vetch "Ostsaat" (*Vicia villosa* Roth.)	1590	16.8	1580	34	27	61	15/16
Sweet pea "seda sec 21" (*Lathyrus sativus* L.)	2060	23.9	1270	36	28	64	22/17
Rye (*Secale cereale* L.)	3330	41.8	1450	39	17	56	42/25
Black oats (*Avena strigosa* Schieb.)	5590	23.2	3080	97	50	147	28/31
Wheat "Mitacoré" (*Triticum aestivum* L.)	1960	78.0	1490	23[a]	24	47	38/26
Oil seed radish (*Raphanus sativus* L.)	4750	13.0	1760	101	34	135	21/20
Rapeseed "Jumbo" (*Brassica napus* L.)	2220	14.8	1980	52	39	91	16/21
Sunflower "Estanzuela" (*Helianthus annuus* L.)	3240	18.2	2300	30	25	55	54/33

[a] Straw only.

Source: Derpsch et al. (1985).

the weed flora (Table 3). The highest weed biomass was measured after wheat, winter fallow, and lupins; the lowest weed biomass was measured after black oats, rye, and oil seed radish.

Other investigations at the Research Institute of Paraná (IAPAR) also show that winter fallow increases weed infestation. The highest percentages of soil cover and number of weeds were measured (7 and 58 days after cutting the cover crops) under winter fallow, while the lowest weed infestation was measured under black oats and oil seed radish (Figure 2). In another study, Derpsch et al. (1988) measured the highest weed infestation after winter fallow and wheat and the lowest after black oats and oil seed radish (Table 4). This shows that oats and oil seed radish are effective cover crops for reducing weed infestation during the winter, and that a monoculture of wheat and widespread winter fallow, on the contrary, permits weed proliferation with the resulting costs to eliminate them.

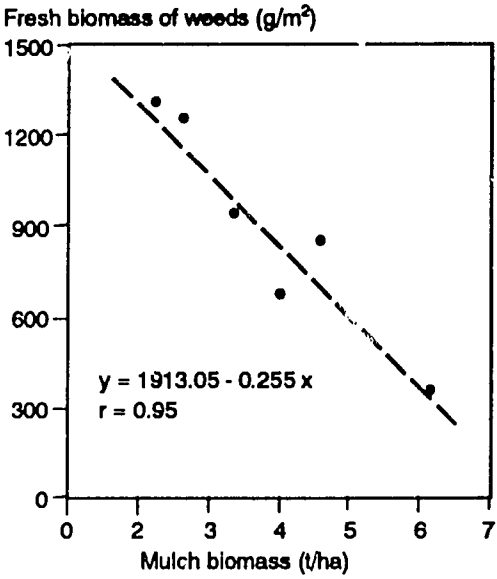

Figure 1. Correlation between mulch biomass of green manure crops at harvest and the weight of fresh biomass of weeds 85 days after cutting green manure crop. Source: Almeida and Rodríguez (1985).

Table 3. Influence of green manure mulches on weed infestation and specific composition of weeds, 85 days after cutting winter crops.

Winter crops	Fresh biomass (g/m²)	*Bplan*	*Dh*	*Bpil*	*Rb*	Others
				Percentage		
Wheat	1347	36	31	5	20	8
Fallow	1541	11	4	63	12	10
Lupins	1613	88	4	3	1	4
Triticale	1269	10	18	15	51	6
Rapeseed	987	44	34	4	11	7
Oilseed radish	861	38	41	3	0	14
Rye	695	13	17	23	33	14
Black oats	361	49	13	13	4	21

Bplan = Brachiaria plantaginea; Dh = Digitaria horizontalis; Bpil = Bidens pilosa; Rb = Richardia brasiliensis.

Source: Almeida and Rodrígues (1985).

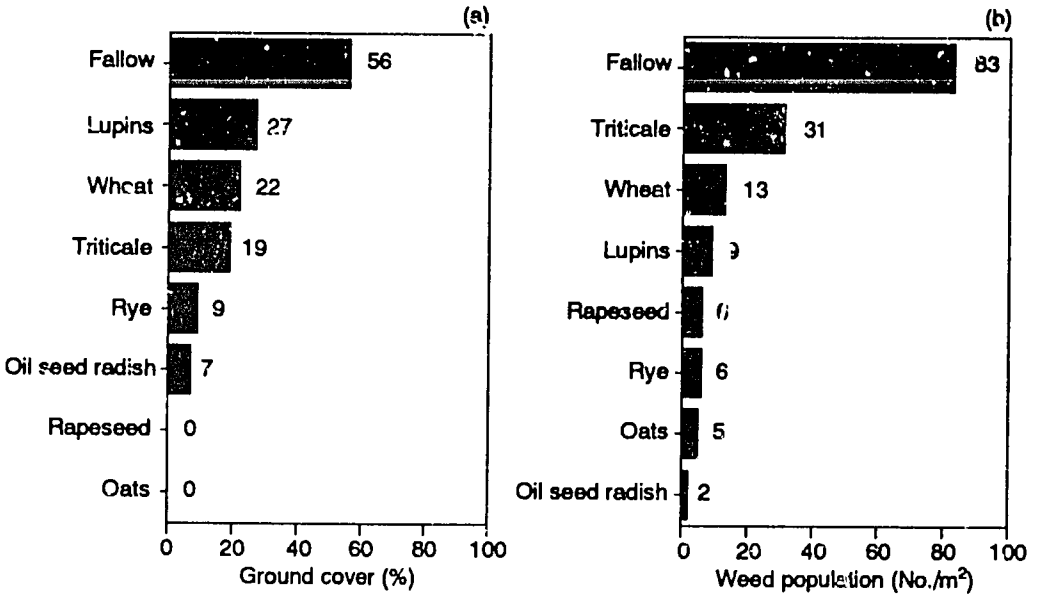

Figure 2. Percentage of soil covered by weeds 7 days after harvest (a) and number of weeds/m² 58 days after cutting green manure crop (b). Source: Almeida and Rodríguez (1985).

Table 4. Weed infestation after different green manure crops, wheat, or fallow (Green manure crops cut on Sept. 3).

Preceding crop	Weed evaluations		
	Sept. 9 Soil cover %	Sept. 30 Fresh biomass gm/m²	Oct. 15 Notes 1-9[a]
Wheat	57	154	7
Fallow	71	296	8
Lupins	9	22	4
Hairy vetch	1	9	2
Sweet peas	5	26	3
Rye	1	6	2
Black oats	0.1	0.2	1
Oilseed radish	0.1	0.2	2
Rapeseed	0.5	16	3
Sunflower	26	28	3

[a] 1 = weedfree, 9 = high weed infestation.

Source: Derpsch et al. (1988).

Influence of Green Manure Crops and Crop Rotation on Soil Conservation and Water Infiltration

Soil cover is a most important factor influencing water infiltration into the soil and consequently soil erosion (Mannering and Meyer 1963, Hudson 1971, Roose 1977, Lal 1982). Therefore, green manure cover crops are an important element in soil conservation and the development of sustainable agricultural systems.

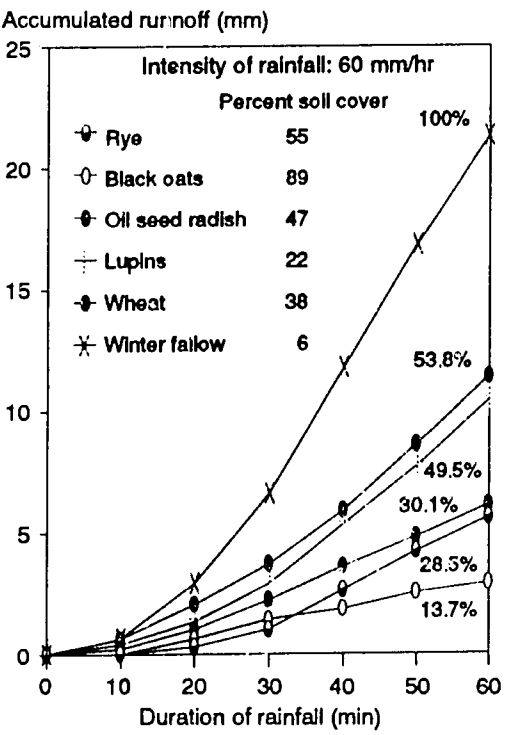

Figure 3. Accumulated runoff as affected by mulches of different cover crops 90 days after cutting. Oxisol, Londrina. Percentages associated with curves are runoff in relation to rainfall after 60 minutes. Source: Christian Roth, pers. comm.

Roth et al. (1987) showed that lowest runoff (13.7% of runoff under fallow), and consequently highest infiltrability, was measured under a mulch of black oats, where 89% of the soil was covered with residues (Figure 3). Rye and oil seed radish mulches also provided relatively good protection. The lowest infiltration rates were found after winter fallow and wheat.

When analyzing the effect of crop rotation on water infiltration (Figure 4), large differences were apparent. Lowest infiltration rates were measured in maize monoculture and winter fallow, while highest infiltration rates were measured in the soybean-lupin-maize-wheat crop rotation—four crops in 2 years (Figure 4).

These results confirm that green manure crops and crop rotation can have a marked influence on water infiltration and consequently on soil erosion. Water that has not infiltrated into the soil will be an erosion hazard.

Residual Effect of Green Manure Crops on the Yield of Succeeding Cash Crops

Experience has shown that farmers will use green manure crops only if yield increases can be expected on the succeeding crop and if costs, labor, and/or machinery requirements can be reduced or other advantages can be obtained in the short term. Therefore, after selecting and testing well adapted green manure crops for a certain location, researchers must determine what effect these have on the yield of following cash crops.

Table 5 shows the short-term residual effect of different green manure crops and wheat on the yield of succeeding soybeans (*Glycine max* L. Merril), kidney beans (*Phaseolus vulgaris* L.), and maize (*Zea mays* L.) in Londrina, in northern Paraná. Highest average yield of soybeans (2.67 t/

ha) was observed after black oats. This yield was 41% higher than the average of all other treatments—37% higher than after winter fallow and 63% higher than after wheat.

The highest grain yields of kidney beans were observed after black oats and oil seed radish when yields were 68% and 52% higher, respectively, than the yields after wheat. Highest yields of maize were obtained after the leguminous green manure crops. Yields after white lupins and hairy vetch (*Vicia villosa* Roth.) were 6.41 and 6.32 t/ha, respectively (increases of over 50%), compared to the yield after wheat. But after sweet peas (*Lathyrus sativus* L.), also a leguminous crop, maize yields of only 4.27 t/ha were attained. On the other hand, high maize yields were

Table 5. Yields of soybeans, beans, and maize as affected by different preceding winter crops in a no-tillage system. Londrina, north Paraná (2-year average except maize).

Preceding Crop	Grain Yield (t/ha)		
	Soybeans	Maize	Beans
Wheat	1.64	4.10	0.44
Fallow	1.35	5.11	0.40
Lupins	1.95	6.41	0.52
Hairy Vetch	1.68	6.32	0.44
Sweet Peas	2.09	4.27	0.50
Rye	1.70	3.14	0.50
Black Oats	2.67	3.53	0.74
Oilseed radish	1.79	5.80	0.67
Rape seed	2.16	4.94	0.54
Sunflower	2.15	3.89	0.43

Adapted from Derpsch and Calegari (1985)

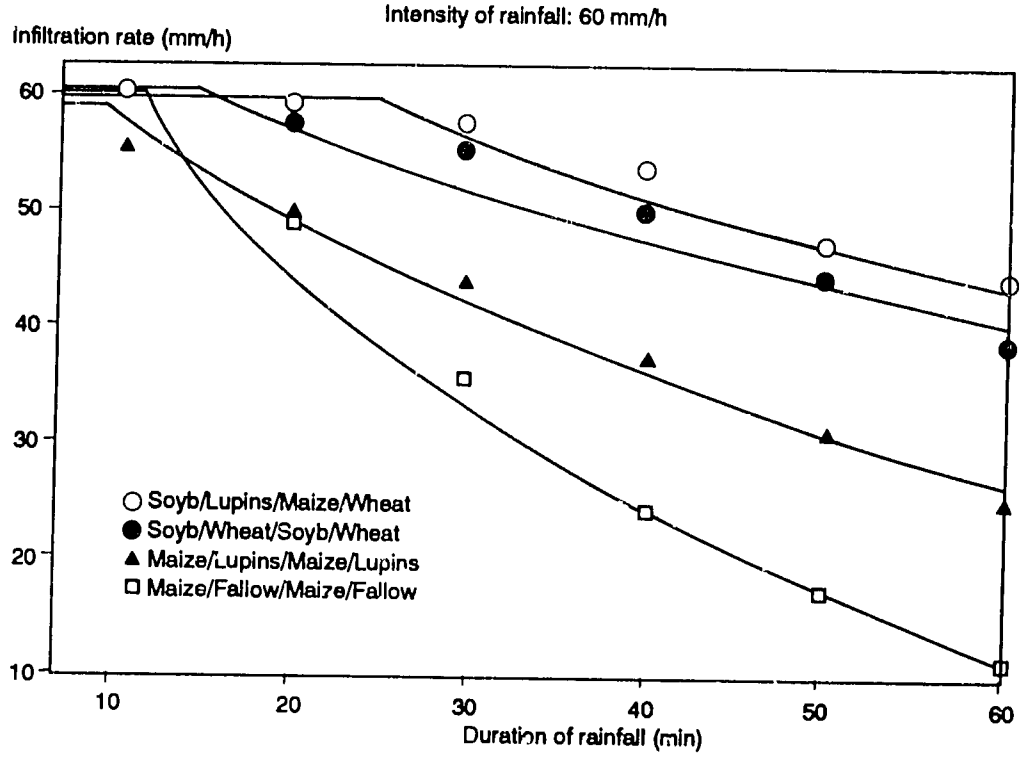

Figure 4. Infiltration rates as affected by different crop rotations and duration of simulated rainfall in a conventional tillage system. Source: Roth et al. (1981).

obtained after oil seed radish, a cruciferous cover crop. High yield in this case can be explained by the high amount of N (135 kg/ha) in the plants (shoots and roots) of oil seed radish measured at harvest time (Table 2).

The results in Table 5 show that green manure crops will not always have a positive effect on the succeeding cash crops, and therefore no general recommendations can be made on their use. Instead, the specific effects of green manure crops on the most important crops have to be determined for each region to learn the place they should have in a rotation. This is in accordance with Calegari (1989)—cited in Muzilli et al. (1989)—who studied the residual effects of green manure crops, wheat, and fallow on the yield of maize in southwestern Paraná. Yield increases of 137% and 114% were obtained in no-tillage and conventional tillage, respectively, when maize followed lupins; yield increases of 124% and 86% were obtained in no-tillage and conventional tillage, respectively, when maize followed *V. villosa* compared to maize after *T. aestivum* (Table 6).

Economics of Green Manure Crops as Compared to Wheat in Rotation with Summer Cash Crops

It has been shown that green manure crops are an important element in a crop rotation and can alleviate negative effects of continuous double cropping or monoculture. Nevertheless, farmers' adoption of technology is more dependent on economic and risk factors than on scientific results.

Table 6. Residual effect of winter green manure crops on the yield of maize, in two tillage systems at Pato Branco, southwestern Paraná (experiment fertilized with P and K, no N).

Green manure species	Tillage treatment for maize			
	No-tillage		Conventional tillage	
	kg/ha	Rel.	kg/ha	Rel.
Leguminous crops				
Ornithopus sativus Brot.	4058	191	4501	195
Vicia villosa Roth.	4743	224	4297	186
Vicia sativa L.	4576	216	4820	208
Lathyrus sativus L.	4344	205	3198	138
Lupinus angustifolius L.	5034	237	4950	214
Gramineae				
Triticum aestivum L.	2122	100	2313	100
Lollium multiflorum Lam.	2313	109	2495	108
Secale cereale L.	1754	83	2557	111
Avena strigosa Schieb.	2224	105	2694	116
Others				
Raphanus sativus	3474	164	3992	173
Spergula arvensis L.	3510	165	3048	132
Winter fallow	3958	187	3813	165

Source: Calegari (1989) cited by Muzilli et al. (1989).

Economic evaluation of green manure crops by Sorrenson and Montoya (1984) shows that using black oats as a winter green manure crop before soybeans can be more economic than planting wheat as a cash crop before soybeans (Table 7). In fact, economic returns from double cropping soybean-wheat were found to be US$218/na (without subsidies for wheat), as compared to US$366/ha after black oats and US$279 after sunflowers (*Helianthus annuus* L.).

Soybean-winter fallow also shows a good economic return with US$291/ha, but this sequence will result in higher erosion risks and weed proliferation. In the case of maize, highest economic returns were obtained when maize followed lupins, oil seed radish, and hairy vetch with US$478, 455, and 446/ha, respectively, compared to returns of US$436/ha after winter fallow and US$251/ha after wheat. Highest economic returns of kidney beans (US$136/ha) were obtained after black oats and oil seed radish compared to only US$67 after wheat and US$62 after winter fallow.

Economic evaluation shows relatively low economic returns when double cropping wheat as compared to a rotation of cash crops with green manure crops.

Table 7. Net benefits (revenue less variable costs in US$/ha/year) of different double cropping sequences in Londrina, Paraná, including wheat, winter fallow, and green manure crops. Refer to yields of cash crops listed in Table 5.

Preceding crop	Soybeans	Maize	Beans[a]
Lupins	205	478	26
Hairy vetch	130	446	-30
Sweet pea	177	215	-37
Rye	184	186	41
Black oats	366	220	136
Wheat, subsidized[b]	298	284	146
Wheat, not subsidized[c]	218	251	67
Oil seed radish	211	455	122
Rapeseed	259	348	45
Sunflower	279	263	20
Winter fallow	291	436	62

[a] Only 1-year experiment.
[b] Average real price paid to farmers 1975-83.
[c] Average landed price of imported wheat in Brazil 1975-83 = future price without subsidies.

Source: Sorrenson and Montoya (1984).

Labor Peaks in Crop Rotation and Monoculture

Farmers adopt crop rotations because they allow better use of available machinery and labor. A wheat monoculture, for example, requires that the entire cultivated area of a farm be planted to the crop in a very short time. When planting wheat and cover crops, there is more flexibility in sowing and harvesting dates, which allows for better labor distribution.

On the grounds of recommended sowing dates for maize in northern Paraná, a maize monoculture results in extreme labor peaks from September 15 to October 31. On the other hand, a soybean monoculture results in extreme labor peaks during the recommended sowing time for this crop (October 15 to November 30). Instead of monocultures of each crop, if half of the area is planted to maize and half to soybeans in rotation, then sowing times can extend over 2.5 months. This can result in higher quality sowing operations, utilization of optimum soil moisture conditions, and reduced machinery (sowing machine, tractor) and labor requirements. The same is valid for operations during the growing season and harvest of these crops as well as for the following wheat crop.

Influence of Crop Rotation on Diseases of Wheat

Spot blotch caused by *Cochliobolus sativus* (anamorph: *Bipolaris sorokiniana* or *Helminthosporium sativum*) is one of the most important wheat diseases in Brazil, Paraguay, Bolivia, India, Bangladesh, and Thailand (Mehta 1985).

Table 8 shows the influence of crop rotation on root diseases of wheat (*Helminthosporium sativum* and *Gaeumannomyces graminis* var. *tritici*) in southern Brazil. It can be seen that

Table 8. Influence of crop rotation on root diseases (*Cochliobolus sativus* and *Gaeumannomyces graminis* var. *tritici*) and wheat yields.

Winter crops				Disease infection	Wheat yield	% of
1979	1980	1981	1982	(%)	(kg/ha)	1982
Wheat *	Wheat	Wheat	Wheat	92	377	100
Wheat *	Wheat	Lupins	Wheat	67	1045	277
Wheat	Oats	Flax	Wheat	19	2184	579
Wheat	Lupins	Rapeseed	Wheat	16	2320	615
Wheat *	Clover	Clover	Wheat	12	2044	542
Wheat	Fallow	Fallow	Wheat	7	2117	562

* = cultivation of wheat or barley.

In summer, soybeans or maize were cultivated.

Source: Reis et al. (1983).

highest disease infection (92%) and lowest yields of wheat (0.38 t/ha) were obtained when wheat was repeated every year on the same field. When wheat was not planted in 1 year out of 4, disease infection was reduced to 67% and yield increased to 1.04 t/ha. Lowest disease infection (7-19%) and highest wheat yields (2.04-2.32 t/ha) were obtained when wheat was replaced by other crops or fallow in 2 out of 4 years. This trial shows wheat yield increases of up to 615% with crop rotation in comparison to a wheat monoculture. Results in this case were obtained in a wet year with rainfalls 34% higher than average. In a dry year, with rainfalls 50% lower than average, crop rotation still resulted in a 33% yield increase (Reis et al. 1983).

Reis and Baier (1983) studied *Cochliobolus sativus* root rot of cereals. Results in Table 9 show that the highest disease rating was measured in wheat and barley while lowest rates were observed in oats.

Table 9. Root disease infection of winter cereals with *Helminthosporium sativum* in naturally infested soil.

Crops	Disease infection (%) (Average of 3 varieties and 4 replications)
Oats	4.2 d[a]
Rye	16.2 c
Triticale	30.8 b
Wheat	46.7 a
Barley	49.7 a

[a] Duncan's Multiple Range Test, P = 0.05.

Source: Reis and Baier (1983).

Reis and Santos (1987) measured the monthly sporulation of *C. sativus* on cereals. Results in Figure 5 show that wheat and barley suffered high infections of *C. sativus* compared to oats, which had a very low infection—although even this low infection may be, according to the authors, an over-estimate due to interplot interference. This again underlines the usefulness of oats in crop rotations either as a green manure crop or for grain production in reducing disease inoculum and infestation in wheat.

Reis and Wünsche (1984) studied the susceptibility of many other plants to root diseases. They found that broadleaf plants are much less susceptible. Among these, white lupins, yellow lupins, as well as clover and rapeseed showed especially low infections.

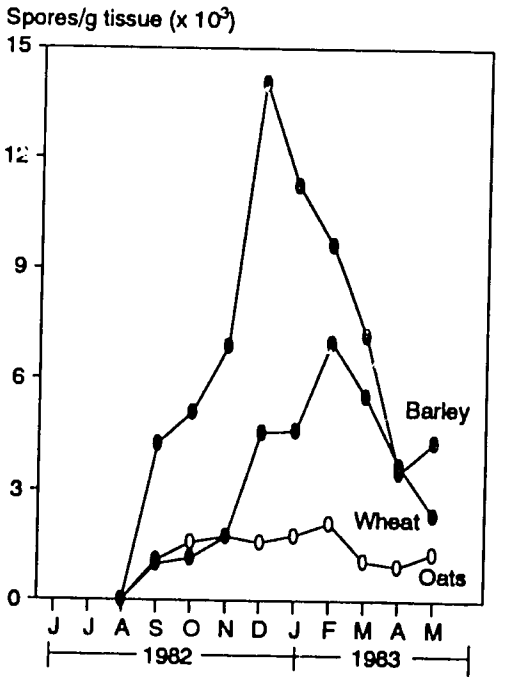

Figure 5. Monthly fluctuation of spores of *Cochliobolus sativus* in the aerial part of barley, wheat, and oats. Source: Reis and Santos (1987).

There is enough evidence from southern Brazil to show that repeating the wheat crop each year on the same land can result in extremely low yields and economic losses due to the survival of necrotrophic parasites (*Cochliobolus*, *Septoria*, etc.) in the residues of the wheat crop (Santos et al. 1987). It has been shown that crop rotation is a very effective means of reducing disease infestation and increasing wheat yields in southern Brazil. Therefore, researchers recommend 2 years without wheat to reduce disease inoculum for the more temperate regions of southern Brazil. Only 1 year without wheat (in rotation with oats) will probably be sufficient in the warmer areas because residue breakdown is faster and root diseases of wheat are less of a problem (Reis et al. 1988).

Since there are only a few alternative cash crops available for planting in place of wheat (i.e., oats, rapeseed, which have a limited market), there is an opportunity for using green manure crops in winter, which can help turn the soybean-wheat sequence into a diversified crop rotation, with all its beneficial side effects.

Influence of Crop Rotation on the Yield of Cash Crops

The Brazilian Agricultural Research Enterprise (EMBRAPA), through the National Research Center for Soybeans (CNPSo) in Londrina, has been conducting research on crop rotations that include wheat in various locations of southern Brazil for many years. In various trials in different regions, it has been shown that continuous wheat cultivation in winter results in significantly lower soybean yields (either double cropped with wheat-soybean or in a summer rotation of maize-maize-soybean-maize-soybean) compared to alternating wheat with fallow or planting white lupins in winter (EMBRAPA-CNPSo 1988, 1989). Significantly lower yields of maize were also obtained under continuous alternation of wheat in a summer maize-maize-soybean-maize-maize rotation compared to continuous lupins or alternating wheat with lupins in winter. Double cropping wheat and soybeans also resulted in highest bulk density and consequently lowest pore volume of the soil compared to crop rotations that included sunflowers, maize, or winter fallow. It was also shown that crop rotations that include winter fallow each year suffer the highest weed infestations. The next highest weed infestation was measured when winter fallow was alternated with wheat.

Other investigations at EMBRAPA-CNPSo (1988) in Londrina showed wheat yields under no-tillage in the lupin-maize-black oats-soybean-wheat-soybean rotation to be 22% higher than in the soybean-wheat double cropping system.

In another trial at Guarapuava in southern Paraná (EMBRAPA-CNPSo 1989), 16% higher wheat yields were obtained when alternating wheat with lupins in winter and soybeans in summer (3.08 t/ha) compared to double cropping wheat and soybeans (2.60 t/ha).

Investigations at IAPAR, Londrina, showed the influence of three crop rotations and N-fertilization on the yield of maize (Derpsch et al. 1988). Yields of maize without N-fertilization were more than doubled in a wheat-soybean-lupin-maize rotation (6.13 t/ha) compared to a maize-fallow rotation (2.56 t/ha). When adding 90 kg N/ha, maize yields in monoculture increased to 6.28 t/ha. This means that the effect of crop rotation and the N contribution of soybeans and lupins preceding the maize crop are nearly equivalent to 90 kg N/ha. The high yield

of maize without N in the four-crop rotation suggests that biological N-fixation of soybeans and especially lupins preceding maize makes mineral N-fertilization on the maize unnecessary. Adding 90 kg N/ha as ammonium sulfate in this rotation resulted in a 0.97 t/ha yield increase of maize. However, a cost-benefit analysis showed that yield increases of at least 0.90 t/ha are necessary to pay for the N-fertilizer cost and its application. Therefore, additional yield increases apparently only cover additional fertilizer costs (Sorrenson and Montoya 1984).

In the same trial, wheat yields were not affected by crop rotation. After the first cycle in 1983, wheat yields were 1.57 t/ha in the wheat-soybean rotation compared to 1.60 t/ha in the soybean-lupin-maize-wheat rotation. In the second cycle in 1985, wheat yields of the first rotation were 2.30 t/ha compared to 2.26 t/ha in the latter (Derpsch et al. 1988).

Although crop rotation did not result in higher wheat yields, benefits for the maize crop are obvious. Results of crop rotations will therefore not always appear when analyzing only yield parameters or the yield of only one crop. To obtain a sound basis for comparison of the different crop rotations, the production systems, as a whole, have to be analyzed (yield, fertilizer needs, tillage, diseases, weed infestation, labor requirements), and economic benefits established.

Economics of a Traditional System Compared to an Improved Production System with Crop Rotation

Sorrenson and Montoya (1989) compared the economics of a traditional crop production system (soybean-wheat and maize monoculture) with an improved production system that involved a 3-year crop rotation (lupin-maize-black oats-soybeans-wheat-soybeans). They also considered different tillage alternatives. Table 10 shows crop gross margins and the weighted averages of the tillage systems. These data are based on 50 experimental years (EY) for maize, 79 EY for soybeans, and 103 EY for wheat. An experimental year of data represents the average yield data collected from a trial for a crop under one rotation and soil tillage system. The weighted average gross margin per year for the traditional technology was US$106/ha. For the 3-year (six crops) crop rotation, starting from the second cycle, the weighted average gross margins per year were US$102/ha for traditional tillage (heavy disk harrow), US$106/ha for conventional tillage with a disk plow, US$112/ha for minimum tillage with the chisel plow, US$146/ha for no-tillage (without considering yield differences), and US$206 under no-tillage (when actual yield differences of tillage treatments were considered, i.e., -1% for maize, +19% for soybeans, and +8% for wheat in the no-tillage system. In fact, when actual yield differences of tillage treatments were considered, then no-tillage and crop rotation resulted in highest crop gross margins already in the first cycle (US$131/ha).

This shows that the use of an integrated crop rotation with two green manure crops and four cash crops in 3 years will only result in higher gross margins than the traditional system when minimum or no-tillage is used. It also shows that in the no-tillage system (and when reported yield differences are considered), annual gross margins of an integrated crop rotation that includes green manure crops can reach US$206/ha—almost doubling the gross margins of the traditional cropping system (US$106/ha).

Table 10. Crop gross margins (US$/ha) in traditional and improved crop production systems.[a]

	Year 1		Year 2		Year 3		Crop gross margins (Weighted average)
Traditional crop production using heavy disk harrow							
67% of area	Soybean	Wheat	Soybean	Wheat	Soybean	Wheat	
	115	6	115	6	115	6	*106*
33% of area	Maize	Fallow	Maize	Fallow	Maize	Fallow	
	73	0	73	0	73	0	
Improved production systems							
First cycle (3 years)							
	Lupins	Maize	Oats	Soybean	Wheat	Soybean	
Traditional tillage	-91	147	-53	151	6	103	*87*
Conventional tillage	-91	145	-46	148	13	101	*90*
Chisel plowing	-91	153	-46	155	13	107	*97*
No-tillage[b]	-91	134	-39	126	7	78	*71*
No-tillage[c]	-91	129	-39	210	33	151	*131*
Second cycle (3 years)[d]							
Traditional tillage	-78	182	-53	151	3	102	*102*
Conventional tillage	-72	180	-46	148	4	103	*106*
Chisel plowing	-72	188	-46	155	4	107	*112*
No-tillage[b]	-60	205	-35	172	43	115	*146*
No-tillage[c]	-60	201	-35	256	69	187	*206*

[a] Subsidized wheat price of US$233.30/t.
[b] No crop yield differences between tillage systems.
[c] Yield differences in no-tillage being considered (-1% for maize, +19% soybeans, +8% wheat).
[d] From second cycle on: 50% less phosphorus fertilization in no-tillage was considered for all crops; less 200 kg/ha urea on maize, plus reduction in residual herbicides on soybeans after oats.

Observation: Erosion losses due to tillage systems were not considered in this economic evaluation.

Source: Sorrenson and Montoya (1984).

Conclusions

- Green manuring and crop rotation are essential elements to increasing water infiltration into the soil, reducing runoff, conserving the soil, and achieving sustainable crop production.

- When appropriate species are chosen, green manure cover crops and their residues can have a major influence in reducing weed infestation and disease inoculum in wheat and increasing yields of the succeeding cash crops

- Economic evaluation of green manure crops shows that, in southern Brazil, black oats as a winter green manure crop before soybeans or kidney beans can be more economic than planting wheat as a cash crop before soybeans or kidney beans. The use of white lupins before maize almost doubled economic returns compared to double cropping wheat and maize.

- While wheat shows rather marginal profitability, its replacement by fallow would be the least desirable option. Alternate crop options are few (oats, rapessed) and opportunities exist for the integration of green manure crops into the rotation in place of wheat in some years.

- Labor peaks can be reduced with the use of appropriate crop rotations. This can result in a better quality of the sowing operation, utilization of optimum soil moisture conditions, and reduction in machinery and labor requirements.

- Crop rotation has resulted in a marked reduction in wheat diseases leading to wheat yield increases of up to 615% over those in a wheat monoculture. Therefore, to break the disease inoculum cycle, wheat should be planted only every second or third year in southern Brazil.

- Crop rotation has resulted in higher yields of cash crops even when diseases were not a limiting factor.

- An integrated crop rotation that includes green manure crops results in higher crop gross margins than the traditional system only when minimum or no-tillage is used.

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Resumen

En este trabajo se analizan los efectos de la rotación de cultivos y la aplicación de abono verde en cultivos comerciales, de acuerdo con los sistemas de producción de trigo mediante el cultivo doble en Brasil. Esta experiencia producirá elementos útiles para la investigación y el desarollo de rotaciones de cultivos en otras partes del mundo. Después de ensayar y estudiar distintos cultivos de abono verde, se encontró que Avena strigosa *Schieb.,* Raphanus sativus *L. Var.* Oleiferus *Metzg. y* Lupinus albus *L. son algunos de los cultivos de abono verne más promisorios para la región estudiada. Se señalan el efecto de distintos cultivos de abono verde en la reducción de la infestación por la maleza, la influencia de esos cultivos sobre la infiltración del agua y la conservación del suelo, el efecto residual de los cultivos de abono verde sobre los cultivos comerciales y los aspectos económicos de los cultivos de abono verde. También se demuestra que las rotaciones adecuadas de cultivos dan como resultado una mejor utilización de la maquinaria y la mano de obra disponibles, reducen las infestaciones por la maleza y las enfermedades y la necesidad de fertilizantes nitrogenados, y contribuyen a la obtención de rendimiento más altos. EL análisis económico revela que, con rotaciones integradas de cultivios que incluyan los de abono verde y prácticas de labranza cero, se puede obtener beneficios brutos anuales más elevados, en comparación con los sistemas tradicionales de producción.*

Nutrient Availability in Degraded Soils of Warm Areas: The Role of Fertilizers in the Process

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Abstract

Soils can be degraded due to many factors, including erosion, loss of nutrients by leaching, excessive soil tillage, imbalanced application of fertilizers, poor irrigation management, etc. In many of these degraded soils, the main problems are nutrient deficiencies and acidity or alkalinity which constrain normal plant development.

In many of the warm lowland soils of tropical Africa, Asia, and Latin America with high annual rainfall, nutrient deficiencies are common with phosphorus, nitrogen, potassium, calcium, magnesium, sulfur, zinc, and boron being the most important. In addition to these problems, low organic matter content and high exchangeable aluminum saturation are common in these soils. Some soils are also high in manganese or iron and sometimes, especially under flooded conditions, rice plants exhibit toxicity symptoms. Physical problems of hardpan or surface crust formation, which restrict water penetration and downward movement, are sometimes present. Soils with excess salts and/or sodium can also present problems of nutrient unavailability, generally P, N, and micronutrients such as Zn, Fe, Cu, Mn, and B.

Fertilizers and amendments play an important role in the solution of these problems. Generally, the topography and physical conditions of these soils are excellent for planting high yielding annual crops, but their chemical properties limit yields of improved varieties. The use of balanced fertilizer applications is of great importance not only to obtain high yields, but also to restore or increase soil fertility.

Introduction

In most areas of the world, yield and production levels are only a fraction of those predicted when the new high yielding cereal varieties of the Green Revolution were released in the 1960s.

Soil-related factors, especially soil acidity, nutrient deficiencies and toxicities, soil salinity and alkalinity, and soil physical conditions, are among the most significant environmental constraints to crop production in warm areas of the tropics (Table 1).

South and Central America

More than 850 million hectares of acid soils, comprising mainly Oxisols and Ultisols and representing 51% of the total land area, exist in Tropical America (Table 2). According to Sanchez and Salinas (1981), the major soil constraints in Tropical America dominated by acidic, infertile soils are deficiencies of phosphorus (P), nitrogen (N), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), and zinc (Zn); low pH; P fixation; aluminum (Al) toxicity; drought stress often longer than 3 months; low water holding capacity; and high levels of erosion (Table 1). In some regions, soils with copper (Cu) and/or boron (B) deficiencies and manganese (Mn) or iron (Fe) toxicities can also be found. Table 3 shows the extent of Zn, Cu, and Mn deficiencies in the Cerrados region of Brazil.

Foliar nutrient analysis is one of the most useful tools to evaluate the current nutritional status of a plant. Table 4 presents data of major and some minor elements from leaf analysis of wheat plants growing in the Brazilian Cerrados. The critical levels presented should be taken only as general indicators of the nutritional status of the plant. More precise, constant critical levels (or ranges) should be established using selective tissue analysis—selection of the youngest fully expanded leaf blade (YEB).

Africa

In Africa, there are approximately 490 million hectares of acidic soils, classified as Oxisols and Ultisols and comprising 27% of the total land area (Table 2). More than 45% of the total land area is covered by acid soils in countries like Zaire, Zambia, and Ivory Coast with problems of high Al saturation (>60%), low available P and low exchangeable K (Tanner 1988). Many of the soils of East Africa are strongly weathered and leached, with low capacities to hold nutrients. In Uganda most of the K is probably associated with organic matter. Potassium release from nonexchangeable sources may be small as in Zimbabwe. Responses to K are also likely on some of the potential wheat soils in the southern highlands of Tanzania, particularly where soils are moderately acidic (IPI 1973).

It appears that micronutrient deficiencies in Tropical Africa are generally related to parent material. Because of the generally low total and extractable levels of B, Cu,

Table 1. Geographical extent of major soil constraints in Tropical America (23°N-23°S) and in regions dominated by acidic, infertile soils.

Soil constraint	Tropical America (1493 10^6 ha)		Acidic, infertile soil region (1043 10^6 ha)	
	10^6 ha	% of total area	10^6 ha	% of total area
N deficiency	1332	89	969	93
P deficiency	1217	82	1002	96
K deficiency	799	54	799	77
High P fixation	788	53	672	64
Al toxicity	756	51	756	72
S deficiency	756	51	745	71
Zn deficiency	741	50	645	62
Ca deficiency	732	49	732	70
Mg deficiency	731	49	739	70
H_2O stress > 3 months	634	42	299	29
Low H_2O holding capacity	626	42	583	56
Low ECEC[a]	620	41	577	55
High erosion hazard	543	36	304	29
Cu deficiency	310	21	310	30
Waterlogging	306	20	123	12
Compaction hazard	169	11	169	16
Laterite hazard	126	8	81	8
Fe deficiency	96	6	?	?
Acid sulfate soils	2	0	2	0

[a] ECEC = exchangeable Al + exchangeable Ca + exchangeable Mg + exchangeable K.

Source: Sanchez and Salinas (1981).

Table 2. Estimates of the area of acidic tropical soils (Oxisols and Ultisols) in selected countries or regions.

Country	Millions of hectares	% of total land area
Tropical America	852	51
Tropical Asia	333	38
Tropical Africa	490	27
Tropics, total	1675	38
Brazil	571	67
Peru	56	44
Colombia	67	59
Venezuela	52	57
Panama	5	71
Mexico	6	3
Indonesia	82	43
Thailand	42	82
Malaysia	24	72
India	43	13
China (tropical)	16	48
Philippines	17	58
Zaire	183	78
Zambia	34	45
Malagasy	21	36
Cameroon	20	41
Ivory Coast	19	58
Nigeria	17	18

Source: IBSRAM (1985).

Mo, and Zn in the soils, deficiencies of these nutrients are prevalent. Boron and Zn problems are commonly observed throughout the region. Deficiencies of Fe and Mn in Tropical Africa are rare. More important is the occurrence of Fe toxicity in flooded rice soils and Mn toxicity in upland soils following acidification resulting from fertilizer use (Kang and Osiname 1985).

Certain dry land areas of North Africa are affected by salinity.

Table 4. Critical nutrient levels in leaves of wheat plants growing in the Brazilian Cerrados.

Element	Dry Matter (%) Low	Medium	Adequate
N	< 2.5	2.5-2.9	3.0-3.3
P	< 0.10	0.10-0.15	0.20-0.30
K	< 1.5	1.5-24	2.5-3.00
Ca	< 0.50	0.5-1.24	1.25-1.50
Mg	< 0.10	0.10-0.19	0.20-0.30
S	< 0.20	0.20-0.34	0.35-0.70
Cu	< 5	-	5-25
Mn	< 5	5-24	25-50
Zn	< 10	10-24	15-30

Source: Adapted from Malavolta and Kliemann (1985).

Table 3. Summary of the range of some micronutrients observed in 518 topsoil samples under "Cerrado" vegetation in Brazil (includes 16 samples under forest vegetation).

Micronutrient[a]	Accepted critical level[b] (ppm)	Samples below critical level (%)	Range	Medium (ppm)
Zn	1.0	95	0.2-2.2	0.6
Cu	1.0	70	0.0-9.7	0.6
Fe	?	-	3.7-74.0	32.5
Mn	5.0	37	0.6-92.2	7.6

[a] Extracted by 0.05 N HCl + 0.025 N H_2SO_4.
[b] According to soil testing services in the State of Minas Gerais, Brazil.

Source: Lopes and Cox (1977).

South and Southeast Asia

In selected countries of Tropical Asia, there are an estimated 333 million hectares of acidic tropical soils, classified as Oxisols and Ultisols and comprising 38% of the total land area (Table 2). These acid soils present problems of N, P, K, Ca, Mg, and S deficiencies and Al toxicity in Indonesia, Thailand, Malaysia, India, China, and the Philippines.

Fertility problems related to saline and sodic soils, such as N, P, Zn, Fe, Cu, and Mn deficiencies and B toxicities, are common in saline soils of Bangladesh, in India, in Pakistan, and in Australia (CIMMYT 1985).

Soils of the arid and semi-arid regions of India are more frequently Zn deficient than those in the humid and subhumid zones. This is also generally true for available Mn, Fe, and Cu (Table 5). Boron toxicity may more often be a problem than B deficiency in soils of the arid and semiarid tropics, particularly in salt-affected soils (Katyal and Vlek 1985).

In India, acid laterites and alkaline black clay soils generally contain low levels of available Mo.

In the humid and subhumid tropics of Asia, a high percentage of the soils are considered Zn deficient. In the Philippines responses to added Zn have been spectacular. Deficiencies of Fe and Mn have rarely been reported for humid and subhumid tropical regions. Copper deficiency is most widespread on the peat soils of Southeast Asia. The majority of the Indian soils are well supplied with B except in certain humid and subhumid areas. In the southern parts of tropical China, B-deficient soils have been found in large areas. Few Mo deficiencies have been reported in soils of humid and subhumid tropical Asia, although a very low foliar-applied dose of Mo on late-

Table 5. Distribution of available Zn, Mn, Fe, and Cu in tropical benchmark soils of India (range and mean in ppm).

		DTPA extractable							
Soil Group	No. of soils	Zn Range	Zn Mean	Mn Range	Mn Mean	Fe Range	Fe Mean	Cu Range	Cu Mean
Arid/semi-arid									
Inceptisols	5	0.2-06	0.4	7.5-48.8	19.0	3.4-22.8	11.6	0.93-6	1.9
Vertisols	9	0.2-1.3	0.4	4.8-16.4	9.8	4.7-9.5	8.0	0.8-2.0	1.4
Alfisols	5	0.3-0.5	0.4	10.3-48.4	24.2	6.7-25.4	17.4	0.9-2.2	1.3
All soils	19	0.2-1.3	0.4	4.8-48.8	16.0	3.4-25.4	11.4	0.8-3.6	1.5
Humid/subhumid									
Inceptisols	4	0.3-1.0	0.8	5.1-102.4	40.4	7.9-51.3	30.4	0.2-4.5	2.5
Alfisols	3	0.2-0.7	0.4	17.5-76.0	45.5	14.3-51.2	34.5	0.2-4.9	2.1
Oxisols	2	0.3-1.4	0.9	18.1-155.4	86.8	19.3-26.3	22.8	0.5-2.9	1.7
Ultisols	1	-	0.3	-	40.1	-	17.5	-	0.5
All soils	10	0.2-1.4	0.6	5.1-155.4	51.0	7.9-51.3	28.8	0.2-4.9	2.0

Source: Katyal and Vlek (1985).

tillering wheat in alluvial soils of West Bengal increased yield by 30% (Katyal and Vlek 1985).

Correction of Important Problems in Acid Soils of Warm Areas

To correct the most important problems of the acid soils of the tropics, the following should be attempted:

- Decrease the Al saturation of the soil (neutralization of acidity).
- Increase the Ca and Mg saturation of the soil.
- Increase the K saturation.
- Increase the level of available P.
- Increase levels of available micronutrients such as Zn and B.

Since Al toxicity and P deficiency are probably the most important problems that constrain wheat production in the acid soils of the tropics, two examples of correcting such nutritional disorders are presented in the following sections:

- Liming to decrease exchangeable Al and to increase exchangeable Ca and Mg in the soil.
- Application of P fertilizers to increase the level of available P in the soil.

Correction of Al toxicity and Ca and Mg deficiencies

In general, soils of tropical regions, especially those classified as Oxisols and Ultisols, exhibit low pH, high exchangeable Al, and high Al saturation (Table 6). Usually, soil pHs are very low (<5.4), but average exchangeable Al in the wheat areas of the tropical regions can vary from 0.46 to 3.1 meq/100 g (Table 6). Aluminum saturation also can be as high as 88% on the Red Latosols of Brazil and as low as 13% on the Ultisols of West Africa (Table 6). Very high Al saturation is present in soils of Australia (72% average, as high as 97%), Brazil (74% average, as high as 90%), and Colombia

Table 6. Exchangeable aluminum, aluminum saturation, and pH of acid surface soils in wheat areas of tropical regions.

Region	Samples (No.)	Soil	pH Range	Exchangeable aluminum (meq/100 g) Range	Av.	Aluminum saturation (%) Range	Av.
Australia	7		4.5-5.2	0.6-3.2	1.6	32-97	72
Brazil	5	Red-Yellow Latosol	4.0-4.6	1.8-3.2	1.7	38-90	74
	3	Red Latosol	4.1-4.2	0.7-1.9	1.2	83-90	88
Colombia	26	Oxisols	4.2-5.1	0.6-5.8	3.1	29-86	68
West Africa		Ultisols					
	21		5.1-5.4	0-2.0	0.46	0-43	13
	26		4.5-5.0	0.05-3.7	1.34	2-69	41
	27		4.0-4.4	0.05-2.8	1.2	1-67	35

Source: Kamprath (1980).

(68% average, as high as 86%). Under these circumstances, wheat varieties are not able to produce more than 10-20% of potential yield (Salinas 1978).

Applications of dolomitic lime (when both exchangeable Ca and Mg are low in the soil) and calcitic lime (when only exchangeable Ca is low) are the best known practices to reduce exchangeable Al so that wheat varieties can produce at levels closer to their yield potentials. Table 7 presents an example of Al saturation reduction on an Oxisol from Brazil and the residual effect of lime applications (Sanchez and Salinas 1981). The reduction of exchangeable Al and increase of exchangeable Ca and Mg vary with time. Figure 1 presents the residual effect of dolomitic lime applied to an Oxisol in Colombia. High rates of lime (6 t/ha) decreased the exchangeable Al from 3 to 1 meq/100 g and increased the exchangeable Ca and Mg. The same was true with lower rates of lime (2 t/ha), but the exchangeable Al only remained low, 44 and 55 months later following the application of 6 t lime/ha. (Gualdron and Spain 1980).

Generally, applying relatively low lime rates to the soil does not affect soil properties deeper than 30 cm. Figure 2 indicates that the main problem with liming is the lack of movement of Ca downward into the profile. In this case, the root zone is restricted to the top 25-30 cm, leading to drought stress and nutritional problems in the wheat plant. The use of gypsum as a source of Ca shows great promise because Ca^{++} accompanied by $SO_4^{=}$ ions moves further down in the profile. Good results have been obtained in Brazil, especially if the gypsum is applied in a mixture with lime (McMahon and Goedert 1985).

Great advances have been made in the genetic aspects for overcoming the problem of Al toxicity in these soils (da Silva 1976). Tolerance to high exchangeable Al in the soil has been incorporated into wheats with high yield potential, but even "tolerant" wheats do not produce well when Al saturation is above 50-60% (Figure 3). A combination of resistant varieties and liming has been successful. Table 8 shows yields results of

Table 7. Residual effects of lime applications on a Brazilian Oxisol in terms of change in topsoil properties and relative grain yields at 6 and 66 months after application.

Lime applied in 1972 (t/ha)	pH (1:1H_2O)		Exchangeable Al (meq/100 g)		Exchangeable Ca + Mg (meq/100 g)		Al saturation (%)		Relative grain yields (%)	
	6[a]	66[a]	6	66	6	66	6	66	6	66
0	4.7	3.9	1.1	1.5	0.6	0.3	63	80	53	50
1	5.0	4.2	0.9	1.1	1.1	0.6	45	61	85	93
2	5.1	4.3	0.5	1.0	1.5	1.0	25	46	88	88
4	5.6	4.8	0.2	0.4	3.1	2.1	6	15	100	89
8	6.3	5.2	0.0	0.1	4.4	4.0	2	2	93	100

[a] Months after lime incorporation. Yields refer to the first crop (maize) and the seventh consecutive crop (soybeans). Maximum yields were 4.0 and 2.1 t/ha, respectively.

Source: Sanchez and Salinas (1981).

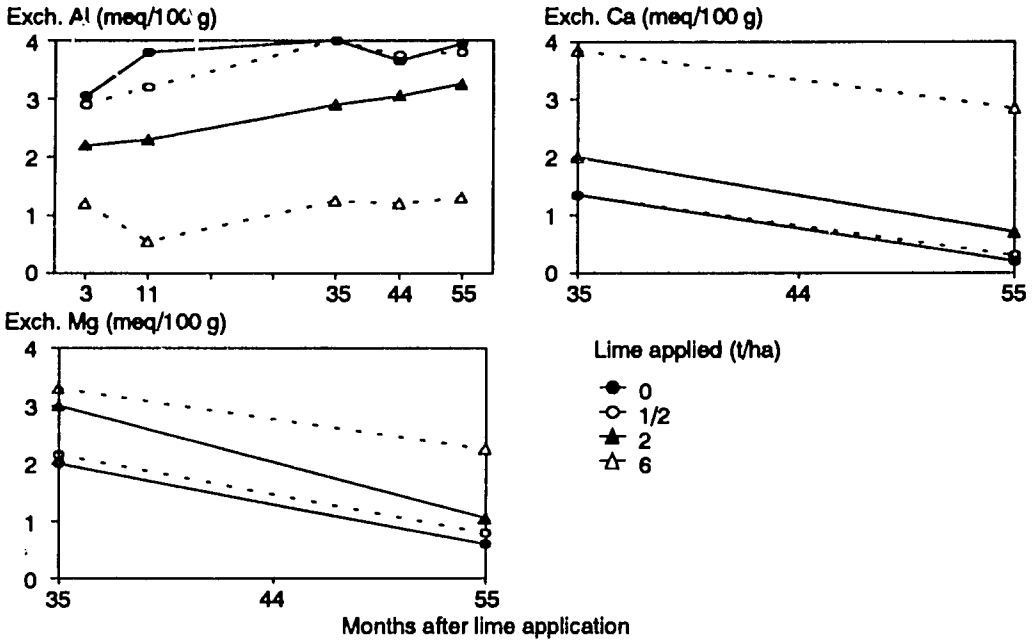

Figure 1. Residual effect of lime (Ca/Mg = 10:1) in an Oxisol of Carimagua, Colombia, from January 1972 to August 1976. Source: Gualdrón and Spain (1980).

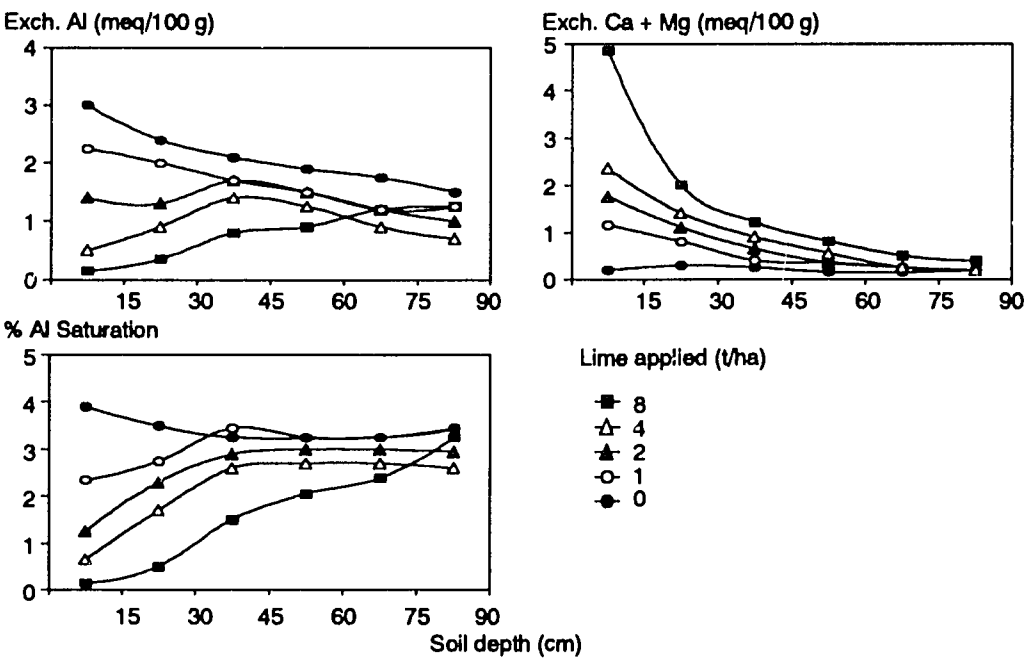

Figure 2. Residual effects of lime incorporation on changes in soil properties with depth 40 months after lime application to the top 15 cm in a Typic Haplustox from Brasilia, Brazil. Source: Sanchez and Salinas (1981).

two wheat varieties, susceptible and tolerant, to three rates of lime applied to a dark-red Latosol from the Brazilian Cerrados. The tolerant variety, IAC-5, produced almost 80% of its yield potential with only 500 kg lime/ha while the susceptible one, Sonora 64, only produced 18% of its yield potential (da Silva 1976). Response to lime applications was also good in the case of the tolerant variety.

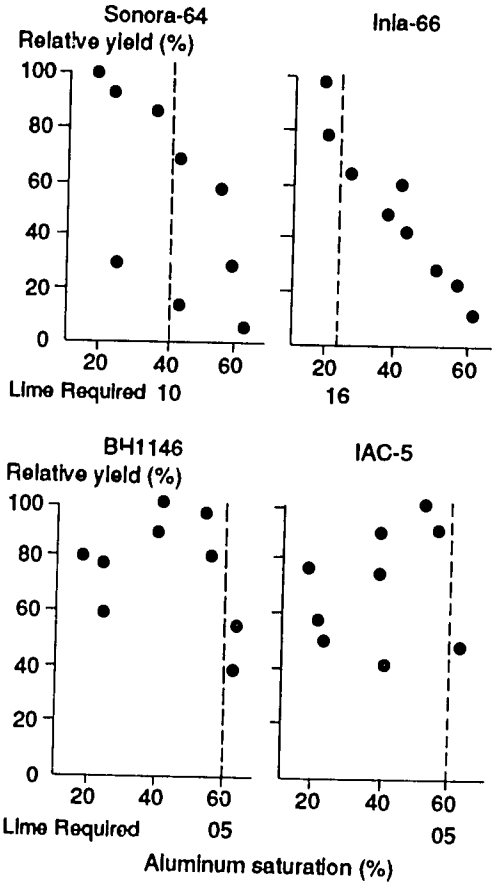

Figure 3. Critical aluminum saturation of four wheat varieties grown in a Brazilian Oxisol. "Lime required" refers to the formula of Cochrane et al. (1980). Source: Salinas (1978).

Correction of low levels of available P in the soil

One of the important soil chemical characteristics of acid soils in the tropics is low available P. Generally, these soils have less than 5 ppm available P (Muzilli and Igue 1976). According to Van Raij et al. (1982), values of 6 and 10 ppm P in loamy and sandy soils in Brazil are considered very low for a wheat crop. To obtain reasonable yields of wheat in these types of soils, it is necessary to apply relatively high doses of some P source and/or use a wheat variety that is highly efficient in the utilization of native and added P.

Where the yield average of wheat in the Cerrados region of Brazil is 1 t/ha, it has been possible to increase that yield more than 100% by adding P to the soil (Goedert and Souza 1984).

There is a strong effect of liming on the response to P application in acid soils of the tropics (Goedert and Souza 1984). With wheat varieties susceptible to Al (Sonora 64) and to a less extent with wheat varieties tolerant to Al (IAC-5),

Table 8. Yield of Sonora 64 (susceptible) and IAC-5 (tolerant) at three levels of Al^{+++} saturation in the soil Latosol vermelho escuro in the Brazilian Cerrados, summer 1976.

Variety	Limestone (kg/ha)	Grain yield (kg/ha)	% of potential yield	Aluminum saturation (%)
Sonora 64	500	127	18	50.0
	2,750	547	78	5.3
	5,000	702	100	0.8
IAC-5	500	967	79	35.2
	2,750	1,103	90	4.0
	5,000	1,223	100	0.2

Source: da Silva (1976).

best responses to P fertilization are obtained when adequate amounts of lime are added to the soil (Figure 4). It is also very important to have well balanced nutrition to optimize the response of wheat to P applications. Figure 5 provides an example of the increased response to P when other nutrients are optimized.

Broadcast applications of water-soluble P fertilizers are not recommended for wheat in low-available P and high P-fixing soils of the tropics (Muzilli 1982). Experiments carried out in Brazil in a wheat-soybean rotation indicate that banding the fertilizer at planting is the best practice for a sound P fertilization for newly developed areas and also for soils with longer cultivation histories (Muzilli 1982).

For many years, soil scientists have been searching for new or local P sources to substitute for the imported water-soluble phosphates, such as triple or single superphosphates and monoammonium or diammonium phosphates. Table 9 presents the results of experiments performed to test several finely ground phosphate rocks from Brazil vs. three well know phosphate sources: Triple superphosphate, Gafsa hyperphosphate and Termophosphate IPT. For wheat, no phosphate rock produced yields comparable to water-soluble phosphates. These rocks are very unreactive (Leon et al. 1986) and can be used as P sources for crops like wheat only when they are partially or totally acidulated with sulfuric or phosphoric acid to produce water-soluble phosphates such as single or triple superphosphates (Leon et al. 1984).

The residual effect of P applied to soils with high P fixation capacity is not very large. One year after the initial application, residual levels are such that yields are only 50% of those of the year when applied (Figure 6). Applications of phosphates to degraded soils not only increase the available P in the soils, but also can improve the availability of other

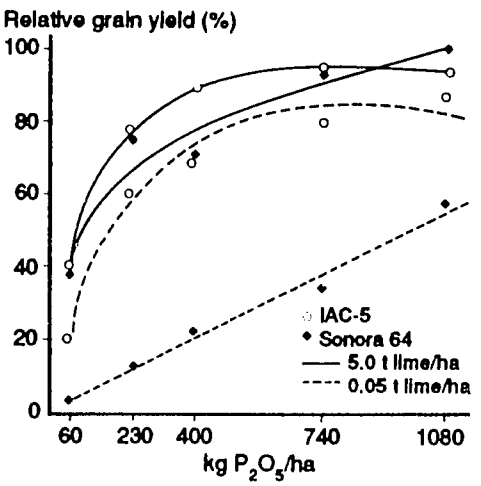

Figure 4. Response of two wheat varieties to broadcast P applications on a dark Red Latosol with two lime applications. Source: Lobato (1982).

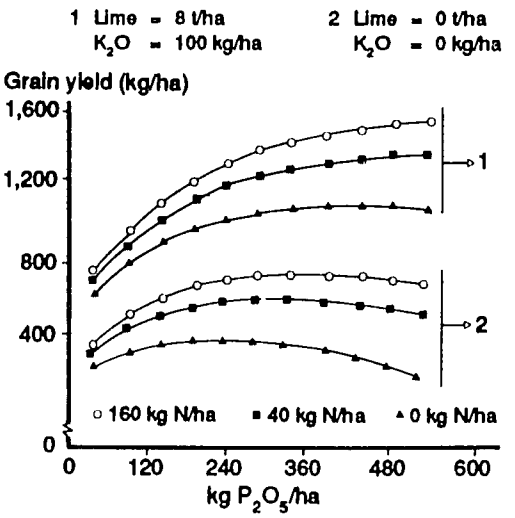

Figure 5. Wheat responses under irrigation to P applications with different levels of N, lime, and K in an LE soil from Brazil. Source: Goedert and Sousa (1984).

nutrients. Figure 7 shows the effect of varying rates of single superphosphate on the exchangeable Ca + Mg in the soil profile 4 years after application. The addition of 140 kg P/ha increased the exchangeable Ca + Mg in the topsoil from 1 to 3 meq/100 g. Substantial increases were also observed at 20- and 40-cm depths (Sanchez and Salinas 1981).

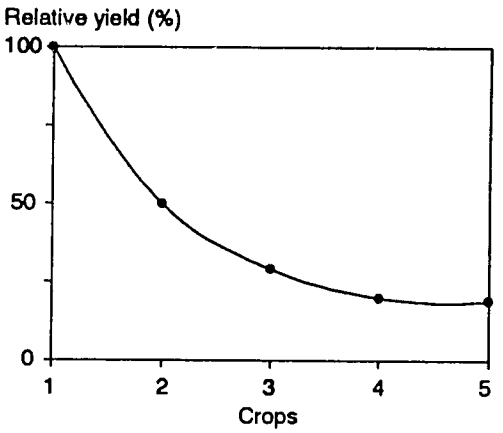

Figure 6. Residual effect of one P application to the first crop. Source: Kochhann et al. (1982).

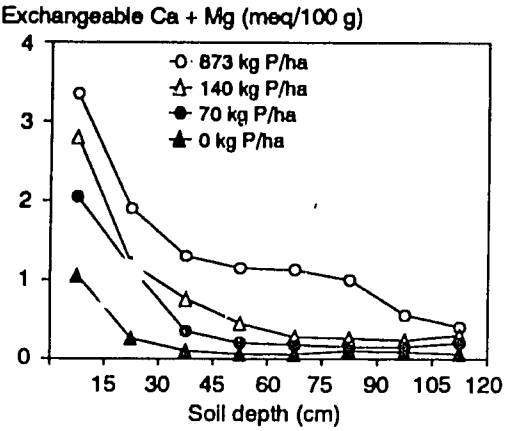

Figure 7. Effect of varying rates of simple superphosphate (as kg P/ha) on Ca + Mg in the soil profile as sampled 4 years after application. Source: Sanchez and Salinas (1981).

Table 9. Average values of relative efficiency (%) of natural phosphates compared with triple superphosphate and hyperphosphate for a rotation of maize, wheat, and soybeans on a dysthrophic Red Latosol in the Brazilian Cerrados.

P source	Maize	Wheat	Soybeans
Triple superphosphate	100 a	100 a	100 a
Gafsa hyperphosphate	106 a	97 a	109 a
Termophosphate IPT	57 ab	91 a	117 a
Maranhao phosphate rock	56 ab	54 a	117 a
Ataxa phosphate rock	56 ab	19 cd	83 b
Patos de Minas phosphate rock	53 ab	11 d	24 b
Alvarada phosphate rock	40 b	50 bc	80 b
Catalao phosphate rock	27 b	0	0
D.M.S. Tukey (5%)	54	34	90
C.V. (%)	33	20	29

Values followed by the same letter are not significantly different.

Source: Muzilli (1982).

Tolerance to high Al saturation in wheat varieties is also related to adaptability to soils low in available P (Figure 8). Tolerant varieties such as BH1146 respond to increases in available P in the soil at high % Al saturation. On the contrary, susceptible varieties such as Sonora 64 only respond to increases in the soil available P when % Al saturation is very low. Sonora 64 does not grow at all when the % Al saturation is high (59%) even though the available P in the soil is high (Sanchez and Salinas 1981).

Conclusions

The potential for wheat production in warm areas of the tropics of Asia, Africa, and South and Central America depends on many environmental factors—soil fertility being one of the most important.

There is a minimal use of fertilizers in the southeast Asian region. In rice-wheat systems, yields are declining in some areas, but yields could be stabilized by fertilization with high levels of NPK and

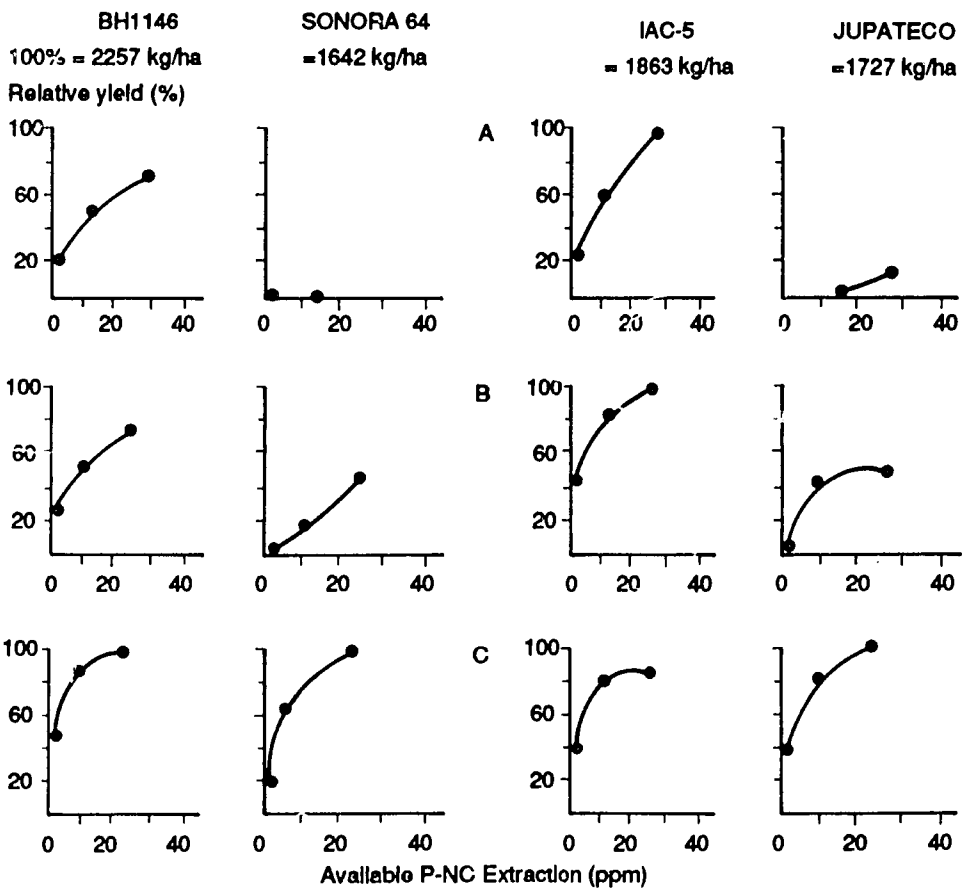

Figure 8. Relative maximum wheat yields as affected by available soil P and Al saturation on levels of a Typic Haplustox from Brasilia, Brazil. A = 59% Al saturation, B = 32% Al saturation, and C = 5% Al Saturation. Source: Sanchez and Salinas (1981).

appropriate micro-nutrients. In the acid soils of Africa and South and Central America, the most important constraints are soil acidity (Al and Mn toxicities) and low nutrient availability, especially P, N, Ca, Mg, K, S, Zn, and B. Wheat production can be successful in the regions of relatively low temperatures and humidity, when appropriate wheat varieties are used and liming and fertilizers are applied to the soils. Long-term application of amendments and fertilizers will further improve the soil chemical characteristics of the acid soils of the warm areas of the tropics and, with the use of improved varieties, will result in increased wheat yields for farmers.

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Resumen

Los suelos pueden degradarse a causa de muchos factores, incluidas la erosión, la pérdida de nutrimentos por la lixiviación, la labranza excesiva, la aplicación desequilibrada de fertilizantes y el manejo deficiente del riego, entre otros. En muchos suelos degradados, los principales problemas son las carencias de nutrimentos y la acidez o la alcalinidad que restringen el desarrollo normal de la planta.

En gran parte de las tierras bajas cálidas de las zonas tropicales de Africa, Asia y América Latina, que tienen elevadas precipitaciones pluviales anuales, son frecuentes las carencias de nutrimentos, de los que los más importantes son el fósforo, el nitrógeno, el potasio, el calcio, el magnesio, el azufre, el zinc y el boro. Además de estos problemas, son comunes el bajo contenido de materia orgánica y una gran saturación de aluminio

intercambiable. En algunos suelos también hay concentraciones altas de manganeso o hierro y a veces, especialmente en condiciones de aniego, las plantas de arroz presentan síntomas de toxicidad. En ocasiones existen problemas físicos originados por encostramiento o una capa dura, que restringen la penetración del agua y su movimiento hacia abajo. Los suelos con exceso de sales y/o sodio pueden tambien presentar problemas de no disponibilidad de nutrimentos, por lo general P, N y micronutrimentos como el Zn, el Fe, el Cu, el Mn y el B.

Los fertilizantes y los correctivos del suelo desempeñan una función importante en la solución de esos problemas. En general, la topografía y las condiciones físicas de esos suelos son excelentes para sembrar cultivos anuales de alto rendimiento, pero sus propiedades químicas limitan los rendimientos de las variedades mejoradas. Las aplicaciones equilibradas de fertilizantes son esenciales no sólo para obtener rendimientos elevados sino también para restablecer o aumentar la fertilidad del suelo.

Breeding Wheats for Tolerance to Micronutrient-Deficient Soils: Present Status and Priorities

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Abstract

This paper explores the use of genetic resources to improve the tolerance of wheats to micronutrient-deficient soils. The agronomic case for doing so is being pieced together. Target soils with chronic micronutrient deficiencies are often high-pH calcareous and alkaline soils in seasonally dry climates, but may include deep sands in any climate. While micronutrient fertilizers are often strikingly beneficial, the yield potential can only be reached if roots penetrate the inhospitable, untreated subsoils. Tolerance (i.e., efficiency) is manifested by greater uptake from deficient soil and the roots must find these elements in their immediate environment for further growth, disease resistance, and access to stored subsoil water. The latter should lead to better water use efficiency and a decelerated advance of dryland salinity.

While wheat does have meaningful diversity for micronutrient efficiency that can be immediately exploited, rye and other members of the Triticinae express even greater efficiency, which may be available to wheat through wide crosses. Generally, bread wheats are more tolerant than durum wheats. The copper efficiency factor (from rye) in our breeders' line Warigal 5RL/4A appears to be adequate for most situations. Iron efficiency in wheat is adequate, whereas manganese efficiency is poor, though it may not be needed at higher temperatures. Although outstanding differences in zinc efficiency among genotypes have been demonstrated in a number of places, little is known of its inheritance. A serious effort to produce Zn-efficient wheats appears to be a priority because Zn deficiency is widely distributed in warmer regions and Zn appears to be strongly linked to disease resistance, tolerance of environmental stresses, and penetration of roots into the subsoil. Additionally, a breeding program is likely to result in higher Zn levels in the grain, an important consideration in human nutrition.

Introduction

In this paper the term "nutrient-efficient" (e.g., zinc-efficient) applies to a genotype or phenotype that is better adapted to, or can yield more in, a deficient soil than can the average of the species. This is an agronomic definition that can be measured in terms of grain yield in a field experiment and does not imply a mechanism. Nevertheless, nearly all efficiency traits so far studied arise from a superior ability to extract the limiting nutrient from soil, rather than a capacity to remobilize the nutrient within the plant or otherwise to survive on less of that nutrient. The thinking in this paper is therefore oriented towards factors that favor absorption.

Since wheat is very efficient for iron, utilizing the bicarbonate-resistant phytosiderophore system that Marschner et al. (1986) called Strategy II, and since boron efficiency in wheat is the subject of another paper in these proceedings, we concentrate here on the transition metals—zinc, manganese, and copper. Many millions of hectares of wheat-growing soils are deficient in one or more of these three metals, notably in China, India, East Africa, northwestern Europe, and Australia. In particular, the subsoils

of the drier regions are highly alkaline making their availability even lower than in the topsoils. Subsoils are of increasing research interest in the seasonally-dry areas because they hold vital stored water, but are almost always highly infertile—and by virtue of their depth, untreatable. A potential genetic solution to the micronutrient problems of top- and subsoils is the subject of this paper.

South Australia enjoys a modified Mediterranean, mild/warm temperate climate with sufficient humidity to promote a modest foliar disease incidence, particularly rusts, with some septoria and powdery mildew.

The Case for a Breeding Program

Plant breeding is a numbers game, and any new objective such as micronutrient efficiency represents a considerable escalation of the breeder's work or else a diversion of effort away from traditional targets such as disease resistance and quality. A strong case is therefore imperative because the lack of compelling arguments for doing so is the reason that little effort has until now been made to adapt crop plants to micronutrient-deficient soils. At the conference in Thailand, Graham (1988a) demonstrated genetic diversity for micronutrient characters within wheat, and further argued that nearly all soils, no matter how poor, had sufficient content of micronutrients stored in the profile. The problem was usually one of availability—a problem that is half soil and half genotype. This brings us back to the agronomic arguments.

Five years ago, on 10 soil types scattered across South Australia, we removed the topsoil and dug up the subsoil from grave-sized pits. Various nutrient treatments were applied to the subsoils as they were returned to the pits in their original layers. The topsoils were then replaced and the sites sown as part of the field, receiving all the farmers' usual treatments and fertilizers, including in some cases, micronutrients. Responses to the nutrients were immediate and often spectacular (Table 1), but generally there was little response to physical disturbance only—or to gypsum, underlining the chemical nature of the problem. Importantly, these responses continue to the present (Table 1; on average, 50% after 3 years); and with the original N most likely lost by now, the residual responses are probably to P and trace elements. Indeed, the micronutrient

Table 1. Response of barley to subsoil fertilizer treatments applied to field plots in 1986 on a calcareous sand at Marion Bay in South Australia: initial responses in 1986 and residual responses in 1988. Physical disturbance had little effect.

	Control[a] (undisturbed)	Physical (disturbed)	Gypsum	Trace elements	Lawn cuttings	NP+TE
1986	100	87	143	145	440	445
1988	100	90	100	190	145	225

[a] Control (100%) = farmers' yield.
Source: Graham and Ascher (1990).

treatment seems to have the greater residual value as time passes. In pot studies we have shown that wheat grows poorly in subsoil even when fertilized with N and P. Although we are experimenting with deep injection of micronutrients through tubes welded down the back of deep-ripping tynes, we believe the correct approach to this problem is to breed wheats with roots that will penetrate subsoils of low P and micronutrient availability. In most respects, P and micronutrients are analogous in the arguments of this paper, but progress with P efficiency is particularly slow, as discussed previously (Graham 1988a).

Immediately relevant to this argument is the picture emerging from physiological studies of roots spanning 4 decades. From the papers of Haynes and Robbins (1948), Epstein (1972), Pollard et al. (1977), Bowling et al. (1978), Graham et al. (1981), Welch et al. (1982), Nable and Loneragan (1984) and Loneragan et al. (1987), it appears that P, Zn, B, Ca, and Mn are all required in the root environment for healthy growth, membrane function, and cell integrity. In particular, P and Zn deficiencies in the external environment promote leaking of cell contents such as sugars, amides, and amino acids, which are chemotaxic stimuli to pathogenic organisms. Although P is phloem-mobile, the other elements are not, or are poorly so; this means that the root tips can not be adequately supplied from elsewhere in the root system, such as for example, from those roots contacting a fertilizer band. Moreover in the case of Zn, a high internal Zn content did not prevent leakiness due to a deficiency of Zn external to the membrane (Welch et al. 1982). It follows that the roots of those wheat genotypes that have a greater capacity to mobilize nutrients strongly bound to soil particles in the rhizosphere will be better able to penetrate the infertile, high-pH subsoil. Evidence of genetic control of penetration of such subsoils is currently being pursued in our laboratories.

It follows too from the above that roots far from a fertilizer band, with leaky membranes, are at greater risk from pathogens. Recent studies have clearly linked trace element deficiencies with enhanced susceptibility to particular pathogens (Graham and Webb 1990). Manganese-deficient wheat plants are more susceptible to *Gaeumannomyces graminis* var. *tritici*, the take-all fungus (Graham and Rovira 1984, Huber and Wilhelm 1988), and to the foliar pathogen, *Erysiphe graminis* (Table 2). Zinc

Table 2. Severe powdery mildew (*Erysiphe graminis*) infection on Mn-deficient wheat plants in pots in the glasshouse is strongly suppressed by small applications of Mn to the soil.

Mn supply (mg/pot)	Total pustules/pot	Pustules /g DWt.	Total pustules/pot	Pustules /g DWt.	Yield (g/pot)
	27 September		18 October		
0	50	100	-	-	0.5
10	657	94	1150	165	6.9
50	492	30	135	8	16.2
100	558	34	164	10	16.6
LSD*	43	1.2			

Source: Graham et al. (1984).

deficiency decreased the resistance of wheat to *Fusarium graminearum*, the crown rot fungus (Table 3), and to *Rhizoctonia solani*, the causal agent of bare patch (Table 4). The implication is that nutrient-efficient genotypes in deficient soil, enjoying better nutrient status, should have greater resistance to these pathogens. This hypothesis is supported by recent studies of take-all with wheats having a range of Mn efficiencies (Figure 1a,b). As the ranking of the genotypes increases from low Mn efficiency (left) to high Mn efficiency (right) in both (a) and (b), so does the extent of take-all lesions on the roots decrease from left to right. Note that this effect of deficient soil is neutralized when Mn is adequately mixed through the soil, although in Figure 1b, the variability in the +Mn plants is yet to be explained. Similarly, a strong association of susceptibility to crown rot (Burgess et al. 1984) with Zn inefficiency (our data) is apparent in the following:

- Zn efficiency: Cook = Takari > Kite > Gatcher > Songlen >> Durati.
- Susceptibility: Cook < Kite < Takari < Gatcher < Songlen << Durati.

Table 3. Effect of Zn supply on severity of crown rot (*Fusarium graminearum*) on 6-week old wheat plants growing in a Zn-deficient sandy soil in pots. Zn strongly inhibited the upward spread of infection.

Measurement	Zn added (mg/plot)		
	0	0.2	6.0
% of all stem sections infected[a]	47	45	28
% of upper stem sections infected[b]	66	34	6
Zn concentration in shoots[c]	7.4	8.2	35

[a] F value for Zn effect = 14.4.
[b] F value for Zn effect = 14.4.
[c] F value for Zn effect = 734.
Source: Sparrow and Graham (1988).

Table 4. Percentage of seminal roots infected by *Rhizoctonia solani* inoculated into a Zn-deficient sandy soil in pots, as affected by Zn fertilizer addition and inoculum density.

Zn applied (mg/g)	Inoculum density (propagules/ kg soil)	
	8	16
0	98	100
12	10	25
LSD*	10	

Source: Thongbai and Graham (1990).

Collectively, these results suggest causality in the concurrence in South Australia of some of the world's most severe root disease and micronutrient deficiency problems.

Topsoil drying is another problem of wheat production on infertile soils of the seasonally humid zone. Most of the micronutrients (and P) is in the topsoil by virtue of fertilizer additions and nutrient cycling. Leaching of the heavy metals is negligible (Jones and Belling 1967). When the topsoil dries as a result of a week or two of dry weather in spring, roots in the nutrient zone are largely deactivated and the plant must rely on deeper roots or retranslocation for further nutrition. With phloem-immobile micronutrients and inefficient genotypes, deficiency can result (Table 5). This occurs in the field (Grundon 1980) where Cu deficiency from topsoil drying at the early boot stage can cause severe sterility problems; these may, however, be overcome by Cu-efficient genotypes such as triticale (Grundon and Best 1981).

Two further advantages accrue to micronutrient-efficient varieties if, by virtue of their efficiency, they also

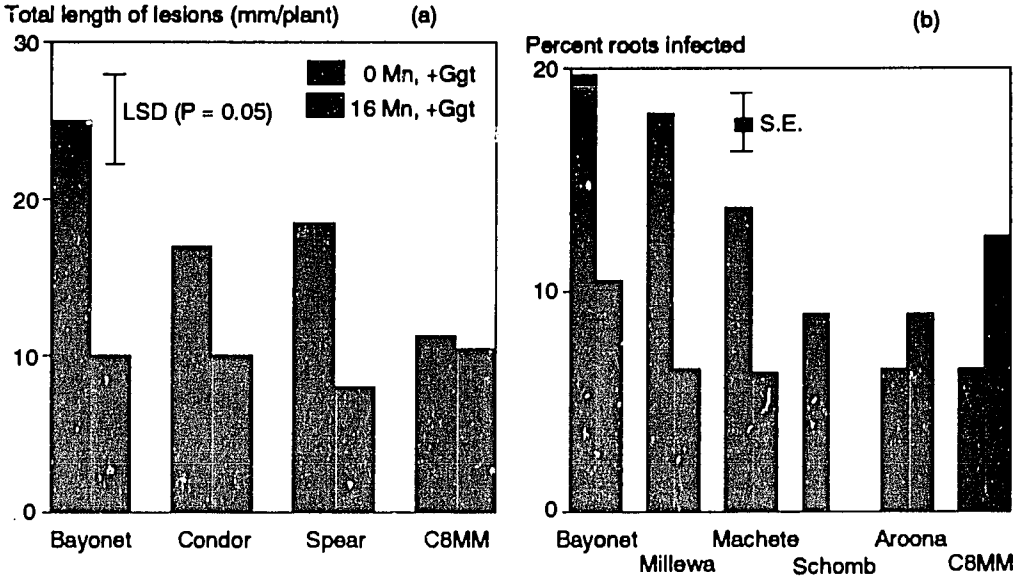

Figure 1. Resistance of wheat cultivars to take-all *(Gaeumannomyces graminis* var. *tritici)* in deficient soil correlates with their manganese efficiency in two studies. Data of Wilhelm et al. 1990, (a). Unpublished data of Judith F. Pedler 1990, (b).

Table 5. Effect of drying topsoil containing adequate added Cu on the sterility of wheat plants, a symptom of Cu deficiency. A pot study using Cu-deficient sandy soil in the glasshouse.

	Straw yield (g/pot)		Grain no. per spikelet	
	-Cu	+Cu	-Cu	+Cu
Topsoil continuously wet	6.3	10.3	0	1.6
Topsoil dry after 2-3 weeks	5.5	7.7	0	0.6
Topsoil dry during development of foliar symptoms (weeks 4-5)		9.6		0.6
Topsoil dry during early stem elongation (weeks 10-13)		9.8		0.8
LSD* (drying treatments)		1.1		0.6

Source: Unpublished data of J.S. Ascher and R.D. Graham (1982).

accumulate more of the limiting nutrient in the grain: firstly, better human nutrition if consumed (Zn especially), and secondly, markedly better seedling vigor when resown on deficient soils. Finally, the degree of micronutrient efficiency currently available is generally adequate to overcome subclinical deficiency.

Screening Techniques

Field testing

Selection in terms of yield is always imprecise and fraught with difficulties. Almost everything in the genome contributes to yield either directly or indirectly. If the selection pressure is great enough, that is, deficiency is severe and the primary limiting factor, then efficient genotypes will be selected on yield, but the prospects of strong interactions clouding selection are always there. For example, in Table 6, the data show inconsistent results between two sites for two lines of barley, one of which, Schooner, was able to respond to October rains by virtue of its later maturity. Under warm soil conditions, it benefitted from improved availability of native Zn in the soil. In this case, we believe the results from the other site, Lameroo, are more typical and reflect better the true Zn efficiency of the lines. Mid-season harvests support this interpretation.

Our main approach to screening is to use plus-and-minus plot pairs to calibrate the performance of a genotype in deficient soil against its own potential with the limiting element supplied. Our primary efficiency index then becomes:

100x(GY-/GY+) or sometimes
100x(veg Y-/veg Y+),
where GY = grain yield, and
veg Y = vegetative yield.

This is the parameter we call "micronutrient efficiency". However, we do not rely on this quotient alone, as for various purposes, the lines with the highest GY- may be of interest when they have outstanding yield potential, but still respond significantly to Zn (e.g., RAC594 in 1988—Table 7). Also of independent interest is GY+, the potential yield for a belt-and-braces approach, that is, a combination of Zn and genotype that, not infrequently, outyields either alone (Graham 1988a). We may say that 100x(GY-/GY+) is probably the best basis for identifying parental material for a breeding program, whereas GY- may be of most immediate interest to producers where the problem is subsoil deficiency or topsoil drying, or where they are not willing to use micronutrients or are unaware of the deficiency.

It is obvious that a genotype can be characterized better by a yield response curve to increasing rates of fertilizer than by simple plus-and-minus treatments. However, in such studies, only a few lines can be reasonably handled before the task becomes too large. Particularly in field experiments, the increased area means increased spatial variability and this is a serious problem with micronutrients whose inherent variability appears to be intrinsically greater than that for macronutrients (Table 8). Moreover, the critical comparison between any given two

Table 6. Zinc efficiencies of two recently released cultivars of barley in two Zn-deficient South Australian soils. Unlike Galleon, Schooner was able to respond to late rains at Yeelanna giving rise to a Zn x season interaction.

Cultivar	Zn efficiency: 100x(-Zn/+Zn)			
	Lameroo		Yeelanna	
	Veg. yield	Grain yield	Veg. yield	Grain yield
Schooner	60	69	71	83
Galleon	61	69	76	56

Source: R.D. Graham, J.S. Ascher, and S.C. Hynes, unpublished.

Table 7. Grain yields and calculated Zn efficiencies of seven wheats grown on Zn-deficient soils at two sites in South Australia in 2 years.

		Lameroo			Yeelanna		
		-Zn	+Zn	100x(-Zn/+Zn)	-Zn	+Zn	100x(-Zn/+Zn)
RAC 594	1988	1.43	1.76	81	2.52	3.18	79
	1989	2.4	2.4	99	3.62	4.11	93
RAC 629	1988	1.26	1.85	68	2.13	2.69	79
	1989	2.49	2.85	87	3.58	3.86	93
Aroona	1988	1.31	1.42	92	2.64	3.01	88
	1989	2.03	2.42	84	3.04	3.43	89
Schomburgh	1988	1.11	1.32	84	2.17	2.28	95
	1989	2.20	2.44	90	3.23	3.61	90
Warigal 5RL	1988	1.04	1.14	92	2.31	2.58	89
	1989	2.22	2.35	94	3.03	3.33	91
Warigal	1988	1.00	1.22	83	2.09	2.65	79
	1989	2.15	2.27	95	2.95	3.23	91
Durati	1988	0.45	1.12	40	1.73	2.14	81
	1989	1.36	1.57	87	2.01	2.32	87
LSD*	1988	0.35			0.40		
	1989	0.45			0.79		

Table 8. Coefficients of variation for each of seven elements analyzed from each of 10 samples taken on a transect across a wheat field. Data are the means for 73 fields, part of a nutritional survey of Mallee regions of South Australia.

Nutrient	Wheat			Barley		
	1986	1987	1988	1986	1987	1988
	CV%			CV%		
P	11	13	11	14	14	9
S	11	10	8	13	10	8
Mg	11	14	13	16	14	11
Mn	24	23	19	24	24	19
Cu	25	19	19	39	19	12
B	34	25	26	44	24	20
Zn	20	18	22	20	19	17

Source: Unpublished data of R.J. Hannam, R.D. Graham, N.S. Wilhelm, J.S. Ascher, and M.J. Webb.

rates (whether it be the plus-and-minus pair or any other pair) will be spread by randomization requirements over greater distances with other treatments between. Provided, therefore, that the site chosen has the degree of deficiency to be targeted in the breeding program, the paired-plot system has the advantage of extreme proximity of the two treatments allowing the most precise determination of 100x(GY-/GY+) and minimal size permitting the comparison of the greatest number of lines. This is the system we have used most in South Australia, but its justification depends on both the selection of relevant sites and on a perception of the number and nature of the genes involved. Thus Paull (1990) found a number of genes involved in resistance to B toxicity and proposed a model (to which Figure 2 is analogous for deficiencies) in order to account for the variable expression of dominance at different selection pressures. In his work, to select for/against all possible segregants in a tetra-genic system, he selected at three different levels of stress.

In deficiency work, it is common to discuss the relative merits of the genotypes with yield-fertilizer rate responses like those in Figure 2. Genotype A is seen to be desirable as it reaches its potential at the lowest level of supply. But with micronutrients, it is common to add 10 to 100 times as much fertilizer as is needed by the crop and this may last (Fe, Mn excepted) for several years. Thus, the lowest rate of nutrient to achieve the yield potential is not determined by the paired-plot system; it can be argued that this is not critical and we need only a point safely on the plateau and a point at zero supply providing the latter results in a meaningful degree of deficiency for the region targeted in the breeding program (for example, y in Figure 2). In this way we have justified our paired-plot approach in the past; and until such times as we have a better idea of the genes and mechanisms involved, it seems the most practical approach for our purposes.

Undoubtedly, the ideal is to understand the mechanisms involved and to select for the desired characters by means of their gene products, whether this be phytosiderophore release as in the case of Fe efficiency in wheat (Marschner et al. 1986), binding affinity in the membrane, root geometry, or composition of simple root exudates that may control the rhizosphere. If Fe efficiency were a problem in wheat, it would appear a simple matter to select for greater ability of the roots to release deoxymugeneic acid under standard conditions of iron stress—as Marschner et al. (1986) have defined. The all-important advantage of this approach is that we are no longer dependent on yield with all its potential for interactions, but are measuring directly the intensity of expression of the efficiency alleles present in that genotype.

Using the paired-plot system

A typical field experiment (using Zn as an example) currently consists of 30

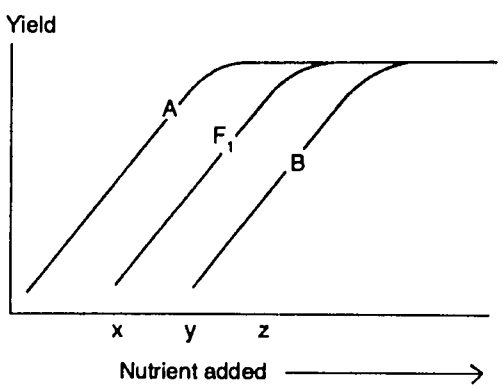

Figure 2. Model of the response to added micronutrient of two parents and their F_1 progeny showing how if screening them at a single level of stress, the genetic interpretation could be at Z, A is dominant; at Y, partial dominance; at X, B is dominant (sensitive parent).

genotypes x±Zn x 5 replications, with border plots. A nearest neighbor, balanced lattice design (Wilkinson et al. 1983), is generated by computer for a 30 x 5 replication design with borders as is done conventionally by breeders. The experiment is then sown with all plots (and borders) entered twice in pairs, one of the pair (chosen at random) receiving Zn. The Waite Institute's cereal breeding system (developed by D.H.B. Sparrow, A.J. Rathjen, and colleagues) uses a magazine system for delivering seed to a cone seeder, and Zn granules are delivered along with the seed via the magazine. The fertilizer box thus contains only basal nutrients (all other nutrients necessary, especially in our environment N, P, S, Cu, Mn, Mo, Co) and does not need to be changed. The Zn granules are commercial zinc oxysulphate (~30% Zn) and are used at several times commercial rates (11-14 g/4.5m^2 plot) because its effectiveness is less than when coated on macronutrient granules (ammonium phosphate), as is the current commercial practice. The soil-applied Zn is supplemented with a foliar spray of $ZnSO_4$ at tillering (equivalent to 200 g Zn/ha). For Mn studies, Mn oxysulphate granules are used followed by one or two foliar sprays at 1 kg Mn/ha. For Cu experiments, we have used $CuSO_4$ granules and foliar sprays at 0.2 kg Cu/ ha).

Mid-season harvests are done if possible, partly to guard against loss of information due to end-of-season events (drought, hail, heavy late rains, farmers' sheep or cattle getting through the fence), and given that we escape the above, grain yield is measured by a Wintersteiger small-plot harvester.

To take advantage of the nearest neighbor (N-N) statistical analysis, which has proved to be more efficient (that is, higher F!), the paired plot data must be reduced to a single variate, namely [GY(-Zn)/ GY(+Zn)]x100 or similar indices. A significant F from this analysis is interpreted as a Zn x genotype interaction, and a higher F is more likely in this analysis than from a simple randomized block factorial analysis. Note that paired-plot borders are required, and since a quotient is the subject of this ANOVA, it is just as necessary to demonstrate that this variate is normally distributed as in a conventional ANOVA. It is also possible to do an N-N analysis of the -Zn plots separately by skipping the +Zn plots and vice versa.

In addition to these analyses of grain yield data and the similar treatment of mid-season vegetative yields, a further index of considerable value is generated, after chemical analysis of the tissues and grain, by calculation of the total uptake of Zn into vegetative growth and/or grain. The most efficient genotypes are so because they absorb more Zn and often (but not always) they maintain higher concentrations of Zn in tissues and/or grain. Uptake, being the product, Zn uptake = yield x Zn concentration frequently shows greater variation among genotypes than yield. By comparison with yield, variation in concentration is conservative.

Pot studies

While we have done considerable work in pots, usually vegetative growth studies, we have sometimes found the rankings quite disparate with field-based grain-yield rankings, which suggests mid-season or later effects can be important (e.g., Marcar and Graham 1987). Moreover, the micronutrient content of seed grown on micronutrient-deficient soil is frequently too low for optimum seedling vigor, and this dictates that screening seedlings for micronutrient efficiency in pots use seeds all from the same source. These effects can carry over in the field to affect grain yield significantly, and so we sometimes recommend that farmers on these soils not keep their own seed.

Screening for Cu efficiency in pots seems to be satisfactory (Graham and Pearce 1979), but although we have done a lot of work on Mn in pots, storage, temperature, and moisture effects on Mn availability are critical and the screening technique (Longnecker et al. 1990) is only partly successful. The mechanism of Mn efficiency has proved quite elusive. We have done relatively little work on Zn efficiency in pots.

The Genetics of Micronutrient Efficiency

The first genetic study of a micronutrient efficiency factor appears to be the classical work of Weiss (1943) on Fe efficiency in soybeans, in which he showed that efficiency was due to a single, major, dominant gene controlling the reducing power of the root surface. Since Weiss' pioneering study, several minor additive genes have been discovered to contribute to Fe efficiency in this crop (Fehr 1982). This situation of a major and several minor genes is likely to be the case generally with the micronutrients. Epstein (1972), who reviewed reports to about 1970, noted apparently simple genetic control of B efficiency in tomato and celery, Fe efficiency in maize and tomato, and Mg efficiency in celery. More recently Fe efficiency in tomato has been shown to be based on a major gene, coding for an Fe-transporting amine, nicotianamine, and a string of minor genes (Brown and Wann 1982, Ripperger and Schreiber 1982).

Copper efficiency in rye appears to be a dominant trait controlled at a single locus on the long arm of chromosome 5R (Graham 1984). It has been possible to transfer Cu efficiency from rye to wheat by means of a translocation of part of 5RL to a chromosome of wheat. Several such translocations exist, but the 5RL/4A translocation appears to be the most satisfactory agronomic type and has been successfully incorporated into adapted cultivars for South Australia (Graham et al. 1987). The 5RL chromosome arm also confers Cu efficiency on triticale unless a Cu-inefficient rye were used in the cross. Triticales generally show agronomically useful Cu efficiency, being intermediate between wheat and rye, and have been used for this reason on many sandy or peaty Cu-deficient soils, and on deficient clayey soils in Queensland to counter the effects of topsoil drying (Grundon 1980).

Work with these 5R materials has shown that Cu efficiency in rye is not clearly linked to Zn efficiency or to Mn efficiency. Thus, independent and relatively specific genes are involved, and root system geometry or size does not appear to be critical. Although rye has a much longer and finer root system than wheat, triticales generally do not (Graham et al. 1981), yet they are usually more efficient for all three elements (Graham 1987, Graham et al. 1987, Harry 1982, Cooper et al. 1988). Studies of rye addition lines suggest that 6R contributes a little to efficiency for all three elements, perhaps by way of a root geometry feature, but the major genes are elsewhere. Manganese efficiency is located on 2R, a conclusion supported by the poor performance on Mn-deficient soils of cv. Coorong, an Armidillo type lacking 2R. By way of contrast, Zn efficiency in rye does not appear to be clear-cut from our studies of rye addition lines of wheat, and may be spread across four or five chromosomes: 2R, 3R, 7/4R, and to a lesser extent, as already stated, 5RL (Table 7) and 6R appear to contribute (Graham 1988a).

Manganese efficiency in barley appears to be simply inherited, taking the evidence of the cross of Weeah (efficient) and Galleon (inefficient) (McCarthy et al. 1988). However, another line WA73S276, which has common parentage with Weeah, has markedly more efficiency than Weeah, suggesting that other loci

may be involved. Moreover, an important parent in Dr. Sparrow's barley breeding program at the Waite Institute, CI3576 from Alexandria is exceptionally susceptible to Mn deficiency, and so is a high percentage of its progeny. At this stage we are not sure whether this is some type of dominant Mn inefficiency trait, or simply very close linkage to a desirable trait in CI3576 which is strongly selected for in the breeding program. A low percentage of wheat cultivars also have exceptional sensitivity to Mn deficiency, the genetic basis of which is also unclear.

Zinc Efficiency Update

Genotypic variation for Zn efficiency in wheat has been recognized and reported by many including Takkar et al. (1988) in the Punjab of India and Hare in New South Wales (Table 9). In South Australia, we also have found considerable diversity for this trait (Table 7). Table 10 shows RAC 594, an advanced Roseworthy line, was the best and most consistent Zn-efficient line over 2 years and two sites. RAC 629 also performed well. Gatcher (and Songlen—data not shown) are two Zn-inefficient bread wheats. Aroona, an early maturing cultivar, was as outstanding for yield and efficiency as RAC 594 in the drier 1988 season, but well below average in 1989 when there was a long, cool finish to the season. Such seasonal effects are quite common. Schomburgh is a rust-resistant backcross derivative of Aroona which

Table 9. The grain yield of Kamilarol relative to that of its parent Durati, in contrasting soils in New South Wales and South Australia. Kamilarol = Durati x Leeds.

	N.S.W. (black clay)		S.A. (light sand)	
	-Zn	+Zn	-Zn	+Zn
100x(GY of Kamilarol/ GY of Durati)	130	105	95	110

Source of N.S.W. data: Dr. Ray Hare, Agricultural Research Centre, Tamworth.

Table 10. Rankings of nine wheats (out of 30) grown on Zn-deficient soil at two sites in two seasons. While some genotypes are stable in various positions, Aroona indicates a strong effect of season. Marion Bay rankings (Mn-deficient) for comparison.

	Lameroo 1988	Yeelanna 1988	Lameroo 1989	Yeelanna 1989	Marion Bay (Mn) 1989
RAC 594	1	2	5	2	15
RAC 629	3	13	2	3	12
Aroona	2	1	20	19	1
Schomburgh	12	11	13	8	5
Warigal-5RL	14	6	12	20	4
Warigal	22	14	16	25	-
Takari	5	23	25	15	27
Gatcher	23	27	27	27	3
Durati	29	25	29	29	23

Source: R.D. Graham, J.S. Ascher, and S.C. Hynes, unpublished.

appears to have lost the Zn efficiency of Aroona. It was consistently an average performer over sites and seasons.

Durati, a very sensitive durum wheat in the heavy black clay soils of New South Wales, was also poor in our light sandy soils. It is, therefore, a valuable indicator line. Kamilaroi is a derivative of Durati (Durati x Leeds) that not only incorporates yield, quality, and disease resistance from Leeds, but also Zn efficiency on the heavy black earths of New South Wales (Table 9). However, in South Australia on light sands, Kamilaroi appears worse than Durati for Zn efficiency (Table 9). Zinc deficiency in the black earths is a complex phenomenon involving very high levels of native soil P and Mn, which appears to aggravate the low Zn status. Thus, Zn efficiency on these soils may not be so much a "foraging capacity of the roots" but a better discrimination for Zn over Mn and phosphate. In South Australia P and Mn are relatively low. We therefore recognize different types of Zn efficiency.

Rye and triticale are generally more Zn efficient than wheat (Harry 1982; K.V. Cooper, pers. comm.). Table 7 shows a slight advantage in Zn efficiency from the 5RL translocation, which also confers marked Cu efficiency to wheat. In particular, Warigal 5RL absorbs more Zn than Warigal and maintains higher concentrations in leaf tissues (Table 11). However, under Zn-deficient conditions, Warigal 5RL had lower Zn concentrations in grain (Table 12).

Besides diversity for yielding ability on Zn-deficient soils, there may be genetic control over Zn concentrations in tissue and grain. From Table 11, RAC 594 and Warigal 5RL are generally superior to the other lines (30 tested in all) in Zn concentration in leaves and Zn uptake at tillering. However, RAC 594 had low grain concentration, a condition apparently linked to its high yield since grain Zn content (g/ha) was high (Table 12). There is a distinct trend, as with grain N, for a lower grain Zn concentration with increasing yield (across genotypes). This is undesirable both because of lower seedling vigor when low Zn seed is used for resowing and because wheat is generally considered to be too low in Zn for adequate human nutrition when it forms a high proportion of the diet (Welch and House 1983). However, Warigal stands out as having the highest grain Zn concentration and content under Zn-deficient conditions. It is highly likely that grain Zn concentrations could be improved by breeding. It should be noted, however, that grain Zn concentration responds dramatically to fertilization under these conditions (Table 12).

Copper efficiency

(Graham 1988a) documented the excellent Cu efficiency of the 5RL/4A translocation line, providing with the parent cultivar (Warigal) an excellent pair of differentials for Cu-deficient situations.

Table 11. Effect of Zn fertilizer on concentrations of Zn and Zn uptake into shoots of six wheat genotypes at tillering stage on a slightly Zn-deficient soil at Yeelanna, S.A. in 1989.

Genotype	Concentration		Uptake	
	-Zn	+Zn	-Zn	+Zn
	mg/kg		g/ha	
Durati	8.9	11.6	3.7	6.4
Machete	8.4	9.4	5.0	7.9
Millewa	9.9	9.6	6.1	7.0
RAC 594	9.3	12.5	5.5	10.2
Warigal	8.1	10.6	4.9	7.7
Warigal 5RL	10.8	11.2	7.1	9.6
LSD*(G)	1.5		1.8	

Source: R.D. Graham and J.S. Ascher, unpublished.

Manganese efficiency

Manganese efficiency is a worthwhile objective in a wheat breeding program where Mn deficiency exists on high pH soils because agronomic solutions to the problem are poor (Graham 1988b). In a matter of days, the residual value of Mn fertilizers on these soils can be decreased by oxidation to 10% of what was added (Marcar 1986). More than that, quite remarkable diversity for Mn efficiency exists within wheat, especially in hexaploids (Table 13) and this may be further supplemented, if warranted, with efficiency genes from rye.

Table 12. Grain yields and grain Zn analyses of lines of wheat at Lameroo 1988, a low rainfall, Zn-responsive sand-over-clay site.

Genotype	Grain yield (t/ha)			Zn concentration (mg/kg)		Grain Zn content (g/ha)		
	+Zn	-Zn	100x(-Zn/+Zn)	-Zn	+Zn	-Zn	+Zn	100x(-Zn/+Zn)
RAC 594	1.43	1.76	81	7.6	25.3	10.8	45	24
Schomburgh	1.11	1.32	84	7.5	23.7	8.3	31	27
Warigal 5RL	1.04	1.14	91	10.5	29.2	10.9	33	33
Warigal	1.00	1.22	82	13.0	26.0	13.0	31	27
Kite	0.95	1.37	69	9.5	24.1	9.0	33	27
TJB*MKR	0.63	1.30	48	12.1	29.5	7.6	38	20
Durati	0.45	1.12	40	9.6	24.9	4.3	28	15
Kamilaroi	0.45	1.29	35	8.8	23.4	4.0	30	13
LSD*(GxZn)	0.31			3.4		4.9		

Source: R.D. Graham, J.S. Ascher, and S.C. Hynes, unpublished.

Table 13. Manganese efficiency of nine wheats grown at Marion Bay in 1989, showing vegetative and grain yields, the efficiencies derived from both harvests, and the Mn concentrations in the young leaves at the first harvest.

Genotype	Vegetative yield (t/ha)			Mn concentration (mg/kg)		Grain yield (t/ha)		
	-Mn	+Mn	100x(-Mn/Mn)	-Mn	+Mn	-Mn	+Mn	100x(-Mn/+Mn)
RAC 594	0.55	1.59	34	7.8	14	0.40	1.43	28
Aroona	0.90	1.45	62	9.5	15	0.83	2.25	37
Halberd*Schom.	0.77	1.19	65	8.7	15	0.80	1.89	42
Machete	0.57	1.16	50	8.1	13	0.62	1.57	39
Warigal 5RL/4A	0.79	1.32	60	8.4	14	0.69	2.05	34
Durati	0.58	1.12	52	7.3	16	0.21	0.98	21
Gj*Wq	0.89	1.14	78	8.4	13	0.29	1.63	18
Takari	0.46	0.98	47	8.2	12	0.15	1.23	12
Millewa	0.29	0.89	32	7.6	12	0.11	1.13	10
LSD* (GxZn)	0.37			2.9		0.42		

Source: Unpublished data of R.D. Graham and J.S. Ascher.

Table 13 shows Mn efficiency varying from 10 to 42% and yields of -Mn plots from 0.1 to 0.8 t/ha. Durati, Takari, and Millewa are so inefficient and the +Mn fertilizer treatment (soil + foliar) so ineffective that the +Mn plots were still deficient (young leaves, 12 mg Mn/kg) and perhaps yielded barely half their potential. This results, although not a great problem, in higher efficiency indices than the inefficient lines warrant, making the extent of diversity for this character actually greater than shown in Table 13. The resistance of Aroona, Machete, and Millewa in these soils to the take-all fungus (Figure 1b) is in line with their manganese efficiency in the vegetative stage (Table 13). Machete, however, improved its ranking from 19th at tillering to 7th at grain harvest, while Gj*Wq faded from 2nd to 21st. While only a few, these lines that changed ranking markedly through the season meant that selecting the top five at tillering would have netted only three of the top five at maturity, a point in favor of selection in the field.

The concentrations of Mn in young leaves, both +Mn and -Mn treatments (Table 13), are generally in line with overall Mn efficiency, but in extensive testing with barley, we have not found this to be a satisfactory selection technique for identifying Mn efficiency in seedlings (Longnecker et al. 1990).

The rankings for Zn and Mn efficiencies are somewhat inversely correlated (Table 10). Some are strikingly different: the Zn-efficient RAC 594 ranks only 15th for Mn efficiency, and Bayonet, Millewa, and Takari are reasonably Zn efficient, but acutely Mn inefficient. A few, however, are reasonably efficient for both (Aroona, Machete) and some quite inefficient for both elements (Durati, Kamilaroi, Songlen, Gatcher). Durati and Kamilaroi are poor for Mn, Zn, and Cu. Indeed, most durum wheats tested are poor for micronutrient efficiencies. Zinc efficiency in wheat, as earlier discussed for rye, appears also to be not closely linked to Cu efficiency.

Conclusions

Breeding wheats with enhanced micronutrient efficiency is a worthwhile objective that can decrease fertilizer requirements, improve seedling vigor, overcome yield losses from unrecognized and subclinical deficiencies, increase resistance to pathogens, and enhance the quality of wheat for human consumption. More than that, micronutrient-efficient wheats may be necessary to permit full exploitation of stored water deep in nutritionally inhospitable subsoils, a response that may not only permit a breakthrough in the yield potential of such semi-arid, high soil pH areas, but may be expected to help to limit the creep of dryland salinity.

Useful genetically-controlled efficiency factors exist in wheat and these may be further supplemented with efficiency genes from rye. However, their exploitation is limited by the high spatial variability of micronutrients, which remains a major experimental problem. For this reason, better selection criteria are needed, but their development is restricted because the mechanisms of these efficiency factors are poorly understood. Although some progress has been made, much more work is needed in this area. Meanwhile, selection may best be done in the field unless existing material is exceptionally poor and of a narrow genetic base.

Zinc and B efficiencies are probably the first priorities for the warm-temperate areas, followed by Cu and at a lower priority still, Mn.

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Resumen

En este trabajo se investiga el empleo de los recursos genéticos para mejorar la tolerancia de los trigos a suelos carentes de micronutrimentos. Se establecen los fundamentos agronómicos que justifican ese empleo. Los suelos con carencias crónicas de micronutrimentos a menudo son suelos calcáreos y alcalinos con un pH elevado en climas con estaciones secas, pero pueden incluir arenas profundas en cualquier tipo de clima. Si bien los fertilizantes con micronutrimentos suelen dar muy buenos resultados, sólo se puede lograr el potencial de rendimiento cuando las raíces penetran los subsuelos inhóspitos no tratados. La tolerancia (es decir, la eficiencia) se manifiesta en una mayor absorción de micronutrimentos en los suelos carentes, pues las raíces deben encontrar esos elementos en su ambiente inmediato para seguir creciendo, resistir a las enfermedades y tener acceso al agua almacenada en el subsuelo. Esto último conduce a un uso más eficiente del agua y a una desaceleración del avance de la salinidad en tierras áridas.

Si bien el trigo posee una considerable diversidad en cuanto a la eficiencia en el uso de micronutrimentos, que puede ser explotada de inmediato, el centeno y otros integrantes de las Triticinae expresan una eficiencia aun superior, que posiblemente se pueda incorporar al trigo mediante las cruzas amplias. En general los trigos harineros son más tolerantes que los duros. El factor de la eficiencia en la utilización del cobre (proveniente del centeno) en la línea Warigal 5RL/4A producida por nuestros fitomejoradores, parece ser adecuado en la mayoría de las situaciones. La eficiencia en el uso del hierro en el trigo es apropiada, pero su eficiencia en la utilización del manganeso es deficiente, característica que tal vez no sea necesaria en temperaturas más altas. Si bien se ha comprobado en varios lugares que existen notables diferencias en la eficiencia en el aprovechamiento del zinc entre los genotipos, se sabe poco acerca de la herencia de esa característica. Un serio esfuerzo para producir trigos eficientes en el uso del zinc debería constituir una prioridad ya que en las regiones más cálidas es muy usual la carencia de ese elemento que al parecer está muy vinculado con la resistencia a las enfermedades, la tolerancia a factores ambientales desfavorables y la penetración de las raíces en el subsuelo. Además, es probable que esa labor resulte en concentraciones más altas de zinc en el grano, un aspecto importante para la nutrición del hombre.

Wheat Breeding for Better Efficiency in Phosphorus Use

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Abstract

Brazilian research has shown large wheat yield responses to phosphorus (P) fertilization. However, in acid soils with high aluminum and manganese contents, a significant proportion of applied P is unavailable to plants. The Campinas Agronomic Institute (IAC) and the National Research Center for Wheat (CNPT) are breeding wheat cultivars for more efficient P utilization. By working with the nutrient in both solutions and soils, it is possible to characterize wheat cultivars for different responses in relation to this character. The experiments developed in nutrient solutions allow the differentiation between P-efficient and P-inefficient cultivars within 15 days. The breeding program developed under field conditions has been successful in transferring the P-efficiency trait from the Brazilian cultivar Toropi to lines adapted to other production regions. The characteristic of greater P uptake in Toropi has been shown to be due to a larger root system that, in acid soils with high aluminum content, allows the plant to explore a greater quantity of soil, which permits the use of P that, apparently, would be unavailable to other genotypes.

Introduction

In 1989, the wheat growing area in Brazil exceeded 3.3 million hectares. More than 50% of this area consists of acid soils with low phosphorus (P) availability and toxic levels of aluminum (Al) and/or manganese (Mn). This complex causes a physiologic disease called "crestamento" (Araújo 1949, Hettel 1989). Commercial wheat production in areas with this type of soil is feasible only when farmers use crestamento-tolerant cultivars. Studies in several wheat growing regions in Brazil clearly show significant yield responses when P fertilizer is applied (Camargo 1972 and 1976, Camargo et al. 1975, Oliveira et al. 1984).

There are at least two alternate solutions to overcome the P-efficiency problem. One is the traditional supplying of nutrients through fertilizer and lime applications. The other is the selection of lines that are adapted to medium-to-low P contents in the soil—and that have an increased efficiency in P uptake and its use. It is important to emphasize that, in acid soils, a high proportion of applied P is unavailable to plants due to P's reactions with Al and iron (Fe). Moreover, in regions with unstable climatic conditions, which result in extremely variable yields, heavy fertilization may not be an economic practice.

Research results demonstrate that there is variability among species and cultivars as to the uptake and use of nutrients (Lyness 1936, Howell and Bernard 1961, Gabelman 1976, Gerloff 1976, and Whiteaker et al. 1976).

Al tends to react chemically with P under nearly every condition (in the soil, solutions, or plants), and while the Al/P interaction has been the subject of extensive studies, the conclusions have

been as diverse as the methods employed (Ali 1973, Rasmussen 1968, and Waisel et al. 1970).

In a study involving nine wheat cultivars in nutrient solutions containing four levels of toxic Al, combined with three pH levels without P, it was demonstrated that a characteristic symptom of Al toxicity—suppression of root development—increased in all cultivars when Al concentration in the solution was increased or when pH was decreased (Camargo 1984). Apparently, tolerance to high Al concentrations is a more relative than absolute characteristic because it depends upon salt concentration, temperature, and pH of the nutrient solutions under study (Ali 1973, Camargo and Oliveira 1981, Camargo et al. 1981, Camargo 1983, 1984).

Fageria and Barbosa Filho (1981) studied the P uptake efficiency of rice under field conditions and were able to select superior material. This higher efficiency was associated with, among other aspects, a deeper and more active development of the root system and to a greater capacity of such cultivars to mobilize fixed P.

Ben and Rosa (1983), when screening Brazilian wheat cultivars for tolerance to crestamento, identified some material that performed better in acid soils with low P availability, which indicated the existence of genetic variability for this factor.

Roner et al. (1988) studied the behavior of nine wheat cultivars in a controlled environment by using a quartz sand as substrate with a nutrient solution having two P levels. They found that root length was unimportant when the P level was high. However, when the P supply was low, differences in root length among cultivars were significant.

The largest research programs in Brazil studying and utilizing the genetic variability of P uptake in wheat are the Campinas Agronomic Institute (IAC), Campinas, São Paulo, and the National Research Center for Wheat (CNPT), Passo Fundo, Rio Grande do Sul. At IAC a significant portion of the work involves nutrient solutions in the laboratory. At CNPT research activities are mainly with soil and directed primarily toward breeding. A partial account of the work at both institutions follows.

Research at IAC

Two experiments had the following goals:

- Experiment 1—To assess P use efficiency of wheat cultivars grown in nutrient solutions containing different P concentrations.
- Experiment 2—a) To study the behavior of wheat, triticale, and rye cultivars in nutrient solutions containing different P levels. b) To study the response of cultivars to increasing levels of P and Al under otherwise identical conditions.

Material and methods

Experiment 1—A split plot design in two replications was utilized with P concentration as the main plots and wheat cultivars as the split plot treatments. Seeds from these cultivars were carefully washed in a 10% sodium hypochlorite solution and placed for germination in Petri dishes for 24 hours. At this point, radicles were beginning to emerge. Thirty uniform seeds of each cultivar were selected and placed on nylon mesh screens over plastic bottles of 8.3-L capacity. Sufficient nutrient solution was supplied so that all seeds and radicles were in contact with the solution.

The final concentration of the solutions was: 4 mM of $Ca(NO_3)_2$, 2 mM of $MgSO_4$, 4 mM of KNO_3, 0.435 mM of $(NH_4)_2SO_4$, 0.3 mM of $CuSO_4$, 2 mM of $MnSO_4$, 0.8 mM of $ZnSO_4$, 30 mM of NaCl, 10 mM of Fe-CYDTA, 0.1 mM of Na_2MoO_4, and 10 mM of H_3BO_3. KH_2PO_4 was added so that four solutions existed with 0, 3.875, 7.75, and 15.5 mg P/L. The pH of the solutions was previously adjusted to 4.0 with 1N of H_2SO_4 and maintained daily during the experiment. Solutions were continuously aerated and the plastic bottles containing the solutions were placed in a waterbath at 25°C ±1°C under fluorescent light.

Plants developed under these conditions for 15 days. When they were removed from the solution, the length of the central primary root of each seedling was measured. Roots and shoots were separated and dried at 45°C for 5 days so that dry matter could be determined. Shoots were analyzed for P, N, K, Ca, Mg, and S contents.

To express the P uptake efficiency of each cultivar growing in these nutrient solutions, the criteria cited by Whiteaker et al. (1976) were observed. The P efficiency ratio (PER) was calculated by dividing shoot dry weight (mg) by the P content of the shoot (mg).

Experiment 2—Genotypes (five wheat, one rye, and one triticale) were studied in nutrient solutions containing five Al levels each at five P levels. Fifteen uniform seeds of each cultivar were placed on nylon screens over jars containing nutrient solution as previously described, but at 10% of the concentration used in Experiment 1 and with 0.1, 3.6, and 10 mg Al^{+++}/L in combination with 0, 3.1, 6.2, 12.4, and 31 mg P/L. The study on P uptake efficiency was carried out with the wheat cultivars only. All remaining procedures were similar to those described in Experiment 1.

Results

Experiment 1—Dry matter yields, root lengths, and shoot analyses for the 10 wheat cultivars grown in nutrient solutions containing 3.875 and 15.5 mg P/L are shown in Tables 1 and 2, respectively. Figure 1 shows the P concentrations of the shoots of the 10 wheat cultivars in four nutrient solutions differing in P concentrations. Table 3 provides the PER values for all cultivars and for the different P concentrations in the solutions.

Experiment 2—Table 4 shows the average root lengths of the studied cultivars measured after 12 days in the nutrient solutions. Table 5 (without Al) and Table 6 (with 3 mg Al^{+++}/L) give the weights of total dry matter, shoots, and roots, as well as P content of the shoots and the PER determined in the nutrient solutions containing different P_2O_5 concentrations.

Conclusions

Experiment 1—By evaluating the wheat cultivars in nutrient solutions containing low P levels, it was possible to separate the genotypes on the basis of P efficiency. Considering the PERs in nutrient solution containing 3.875 mg P/L, the cultivars IAC 5-Maringá, IAS 20, BH1146, and IAC 17 could be considered efficient in P utilization; IAC 18, IAC 13, and IAC 15 were intermediate; Siete Cerros, INIA 66, and Alondra S 46 were shown to be P inefficient.

By using increasing P levels, it was possible to determine those genotypes that respond to higher levels of the nutrient in a very short time. IAC 5-Maringá, IAC 18, and INIA 66 responded with increased shoot growth as P availability increased; IAC 20, IAC 13, Siete Cerros, and Alondra S 46 exhibited a moderate response; the remaining cultivars showed no response.

Table 1. Shoot and root dry matter, root length, and shoot chemical analyses of 10 wheat cultivars grown for 15 days in nutrient solution containing 3.875 mg P/L. IAC, Campinas-SP.

Cultivars	Dry matter			Root	Shoot analyses						
	Shoot (mg)	Root (mg)	Tot. (mg)	length (mm)	P (%)	P (mg)	N (%)	K (%)	Ca (%)	Mg (%)	S (%)
IAC 5-Maringá	1,380	348	1,728	282	0.480	6.59	6.67	5.51	0.38	0.33	0.287
IAS 20	919	264	1,183	241	0.536	4.91	6.30	5.29	0.39	0.34	0.273
BH 1146	1,251	360	1,611	297	0.547	6.34	6.22	5.57	0.41	0.35	0.245
IAC 17	939	299	1,238	267	0.552	5.20	6.52	5.36	0.38	0.34	0.276
IAC 18	1,033	285	1,318	259	0.571	5.89	6.79	5.41	0.42	0.37	0.245
IAC 13	823	196	1,019	199	0.587	4.76	6.94	5.46	0.43	0.37	0.279
IAC 15	820	260	1,080	216	0.589	4.80	6.69	5.20	0.36	0.34	0.309
Siete Cerros	729	178	907	179	0.609	4.44	7.29	4.97	0.36	0.34	0.272
Alondra S 46	950	236	1,186	245	0.623	5.93	6.64	5.89	0.43	0.37	0.260
INIA 66	860	208	1,068	239	0.648	5.57	6.92	5.37	0.35	0.34	0.248
F	4.6*	6.3*	4.8*	12.3**	7.8**	3.3*	2.7	1.2	5.4**	2.1	1.0
C.V.%	13.8	14.3	13.5	6.1	4.3	11.5	4.1	5.8	4.7	4.9	10.7
d.m.s. (5%)	544	153	660	58	0.097	2.50	1.07	1.24	0.07	0.07	0.114

Table 2. Shoot and root dry matter, root length, and shoot chemical analyses of 10 wheat cultivars grown for 15 days in nutrient solution containing 15.5 mg P/L. IAC, Campinas-SP.

Cultivars	Dry matter			Root	Shoot analyses						
	Shoot (mg)	Root (mg)	Tot. (mg)	length (mm)	P (%)	P (mg)	N (%)	K (%)	Ca (%)	Mg (%)	S (%)
IAC 5-Maringá	1,490	325	1,815	272	0.93	13.79	5.82	5.47	0.75	0.34	0.207
IAS 20	933	271	1,204	250	0.83	7.78	6.25	5.85	0.77	0.33	0.224
BH1146	1,223	345	1,568	290	0.97	11.87	6.10	4.70	0.81	0.35	0.225
IAC 17	928	287	1,217	257	0.89	8.15	6.22	4.86	0.76	0.34	0.229
IAC 18	1,180	309	1,488	281	0.97	11.50	5.94	5.95	0.83	0.38	0.196
IAC 13	857	189	1,046	194	1.03	8.75	6.74	5.08	0.86	0.37	0.223
IAC 15	787	212	999	206	1.09	8.56	5.82	5.18	0.72	0.34	0.267
Siete Cerros	744	181	925	181	0.99	7.40	7.30	5.43	0.72	0.35	0.205
Alondra S 46	960	259	1,219	245	1.11	10.68	6.24	5.70	0.86	0.39	0.251
INIA 66	972	219	1,191	245	1.06	10.32	6.36	5.50	0.69	0.32	0.223
F	10.3**	3.4*	8.1*	13.3**	2.9	10.66**	3.3*	1.2	4.3*	15.1**	2.0
C.V.%	9.9	17	10.9	6.3	7.5	9.2	5.2	10.2	4.9	3.6	9.5
d.m.s. (5%)	406	175	546	57	0.294	3.59	1.31	2.17	0.08	0.05	0.085

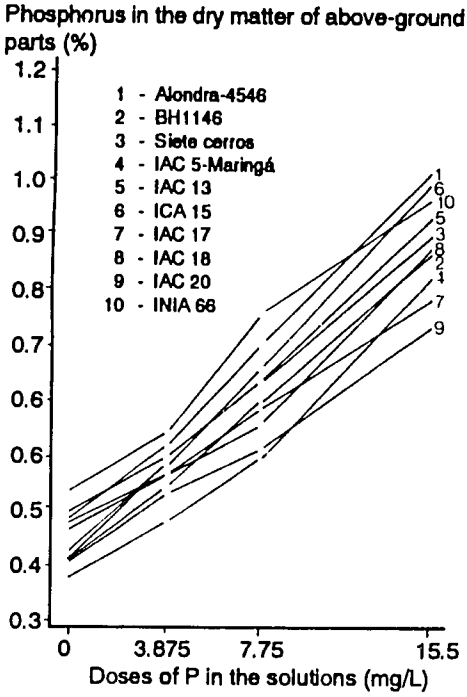

Figure 1. Phosphorus in the dry matter of above-ground parts of 3 plants each of 10 wheat cultivars studied when submerged for 15 days in nutrient solutions containing 0, 3.875, 7.75, and 15.5 mg P/L. IAC, Campinas, São Paulo.

Experiment 2—The nutrient solution technique with differing Al levels employed in the differential study of wheat, rye, and triticale cultivars made it possible to quickly differentiate which cultivars were tolerant and which were susceptible to Al toxicity. Rye and triticale cultivars showed greater Al tolerance than did wheat. Considering root growth differences between Al concentrations of 3 and 10 mg Al^{+++}/L, the wheat cultivars BH 1146, IAC 5-Maringá, IAC 21, and IAC 24 were classified tolerant and Anahuac was susceptible.

Al toxicity symptoms were induced in all cultivars by increasing Al and P concentrations in the treatment solutions.

The shoot dry matter production and PER in solutions of increasing P concentrations suggested that IAC 5-Maringá and IAC 21 were efficient, IAC 24 intermediate, and Anahuac inefficient. When 3 mg Al^{+++}/L were added to the solutions, IAC 5-Maringá was considered efficient, IAC 21 and IAC 24 moderately efficient, and Anahuac inefficient.

Table 3. Phosphorus efficiency ratio (PER) of 10 wheat cultivars grown for 15 days in nutrient solutions containing different P concentrations. IAC, Campinas-SP.

Cultivars	PER			
	0 mg P/L	3.875 mg P/L	7.75 mg P/L	15.5 mg P/L
IAC 5-Maringá	269	209 a	166 a	108
IAS 20	247	187 ab	162 ab	120
BH1146	247	183 abc	142 cde	104
IAC 17	211	182 abc	145 cd	113
IAC 18	219	175 bc	151 bc	103
IAC 13	237	172 bc	134 def	98
IAC 15	246	171 bc	131 ef	92
Siete Cerros	201	165 bc	135 def	101
Alondra-S-46	206	161 bc	124 fg	90
INIA 66	189	155 c	116 g	95
F	2.9	8.9**	57.5**	3.1
CV%	9.4	4.1	2.1	7.3
LSD (5%)	84	29	12	30

Data followed by the same letters do not differ significantly, DMRT, P = 0.05.

Table 4. Average root lengths (mm) of five wheat cultivars, one triticale, and one rye, grown in complete nutrient solutions containing five P levels at five levels of Al. IAC, Campinas-SP.

Cultivars	P concentration (mg/L)	Al^{+++} concentration (mg/L)				
		0	1	3	6	10
BH1146	0.0	155.9	126.5	97.3	46.8	29.6
	3.1	170.1	105.3	112.8	45.6	25.5
	6.2	169.3	120.8	117.2	51.2	28.3
	12.4	149.5	163.8	1108.0	28.3	13.8
	31.0	166.8	209.4	1106.8	10.5	13.8
Anahuac	0.0	114.8	12.7	9.9	11.8	8.8
	3.1	158.2	10.7	13.3	13.1	8.6
	6.2	158.1	20.6	12.8	9.7	7.4
	12.4	155.6	53.0	11.1	8.9	9.5
	31.0	136.6	87.3	13.5	9.2	6.1
IAC 5-Maringá	0.0	141.2	139.3	70.2	37.6	24.4
	3.1	166.9	103.9	101.1	34.3	16.3
	6.2	159.8	95.3	91.3	41.9	24.2
	12.4	133.5	132.2	107.6	20.6	17.2
	31.0	143.6	140.2	94.9	14.4	15.4
IAC 24	0.0	101.5	89.5	73.6	39.6	16.9
	3.1	113.6	75.3	78.8	39.5	27.6
	6.2	121.2	90.6	78.9	45.4	19.7
	12.4	116.7	80.6	89.1	28.0	12.9
	31.0	113.7	105.2	74.8	17.1	11.6
IAC 21	0.0	117.0	133.9	85.9	34.7	23.0
	3.1	149.4	106.7	89.3	34.9	20.7
	6.2	144.5	106.1	87.3	49.7	23.4
	12.4	136.0	132.8	94.6	28.5	14.5
	31.0	125.5	172.8	85.4	16.4	13.4
TCEP 77138 (Triticale)	0.0	123.1	115.7	113.3	63.5	53.8
	3.1	124.4	111.8	60.9	60.9	53.7
	6.2	137.8	140.6	128.8	56.3	46.9
	12.4	124.9	135.0	125.3	23.2	33.4
	31.0	106.7	119.2	104.3	18.7	8.3
Rye	0.0	110.2	141.1	119.4	49.5	55.2
	3.1	106.1	118.1	106.3	59.5	53.0
	6.2	109.1	139.5	89.8	77.8	53.2
	12.4	110.9	161.8	138.7	31.4	52.3
	31.0	95.9	96.9	150.9	45.3	23.9
L.S.D. P = 0.05		62.1	36.0	31.5	13.5	12.2

Table 5. Shoot and root dry weight, P content of the shoot, and the PER, as affected by P concentration in the absence of aluminum in the nutrient solutions. IAC, Campinas-SP.

Cultivars	P concentration (mg/L)	Dry matter Shoot (mg)	Root (mg)	Total (mg)	P content of shoot %	mg	PER Shoot mg/ P mg
IAC 5-Maringá	0	580	270	850	0.211	1.22	474
	3.1	660	266	926	0.263	1.74	380
	6.2	720	279	999	0.335	2.41	299
	12.4	684	235	918	0.469	3.21	213
	31.0	696	244	940	0.670	4.66	149
IAC 21	0	593	244	837	0.237	1.41	421
	3.1	604	245	849	0.237	1.43	422
	6.2	697	246	943	0.273	1.90	366
	12.4	734	273	1007	0.505	3.71	198
	31.0	524	183	706	0.716	3.75	140
IAC 24	0	362	132	494	0.299	1.08	334
	3.1	366	135	501	0.351	1.28	285
	6.2	360	115	475	0.423	1.52	236
	12.4	386	136	522	0.659	2.54	152
	31.0	373	131	506	0.969	3.61	103
Anahuac	0	373	132	505	0.434	1.61	230
	3.1	441	202	643	0.443	1.96	226
	6.2	462	158	620	0.542	2.50	185
	12.4	430	160	590	0.743	3.20	135
	31.0	372	102	474	0.830	3.09	120

Table 6. Shoot and root dry weight, P content of the shoot, and PER as affected by P concentration with 3 mg/L of aluminum in the nutrient solutions. IAC, Campinas-SP.

Cultivars	P concentration (mg/L)	Dry matter Shoot (mg)	Root mg	Total mg	P content of shoot %	mg	PER Shoot mg/ P mg
IAC 5-Maringá	0	580	190	770	0.216	1.253	463
	3.1	677	219	896	0.206	1.395	485
	6.2	696	217	913	0.412	2.866	243
	12.4	690	220	910	0.381	2.629	262
	31.0	680	230	910	0.742	5.046	135
IAC 21	0	573	208	781	0.185	1.060	541
	3.1	563	208	771	0.299	1.682	334
	6.2	620	217	837	0.340	2.107	294
	12.4	596	202	798	0.474	2.826	211
	31.0	635	188	823	0.618	3.927	162
IAC 24	0	320	110	430	0.247	0.790	405
	3.1	340	130	470	0.309	1.051	324
	6.2	393	155	548	0.350	1.375	286
	12.4	369	155	524	0.288	1.063	347
	31.0	435	130	565	0.742	3.226	135
Anahuac	0	313	83	396	0.326	1.019	307
	3.1	300	120	420	0.426	1.278	235
	6.2	302	94	396	0.495	1.495	202
	12.4	292	94	386	0.460	1.342	217
	31.0	333	136	469	0.593	1.976	169

Research at CNPT

Breeding wheat for better P efficiency

CNPT initiated research on developing cultivars with superior P efficiency in 1980. Initially, attempts were made to identify, among cultivars showing a greater tolerance to crestamento, genotypes that performed better when grown in soils with toxic levels of Al and P. From this work, the old cultivars Toropi and PG 1 were identified. Possibly, during the early breeding work in Brazil, when fertilizer purchase was very difficult, breeders had unconsciously screened not only for tolerance to crestamento, but also for the efficient use of available P.

Ben and Rosa (1983) compared Toropi and PG 1 with other cultivars, using several P levels, and confirmed their better utilization of applied P. Based on these results, CNPT started a breeding project in 1981 aimed at incorporating P efficiency into genotypes with high yield potential—initially without considering disease resistance.

Crosses and backcrosses were made using Toropi and PG 1. Commencing with the F_3, the segregating material was selected in the field in soils with a pH of 4.6, P levels between 1.0 and 3.0 ppm, K at 85 ppm, exchangeable Al at 2.4 mg/100 g of soil, and an organic matter content of 4.5%. Only N fertilizer was applied. Under these very severe conditions, the surviving plants were selected. During the summer, generations were advanced in a fertile soil. A sample from every population was also grown in soils having better fertility in order to avoid genotype loss. Following this methodology, the material was screened up to the F_6 generation, at which stage, the material was subjected to more than one P level.

As the program developed, it was observed that, when using soil with toxic Al and Mn levels, the genotypes showed different responses when P (up to 20 ppm soil P) was applied immediately before sowing to that when sowing was done without applying P (residual P available only). Toropi utilized P, made difficult to uptake by Al^{+++}, much better than other cultivars identified as crestamento tolerant. Since then, the segregating material has been selected under the latter fertility situation. Using this procedure, material was selected that could make better use of fixed P, a very common characteristic in acid soils. According to Volkweiss and Raij (1976), in a Santo Angelo soil, very similar to that at Passo Fundo and with a pH of 4.9, 97% of applied P is fixed. When the soil was limed (6 t/ha) to attain a pH of 5.9, 95% of the applied P is fixed.

Since 1985, segregating materials have been sent to Mexico during the summer for evaluation at Ciudad Obregon where, under high management inputs and favorable environment conditions, yield potential can be determined. The selected materials are then returned to Brazil for evaluation under Passo Fundo conditions. This shuttle breeding system continues through all segregating generations.

At the same time, attempts are being made to identify other sources of P efficiency. Following the work of Koehler (1983) at Washington State University, 23 cultivars were introduced from the USA, which, along with Alondra'S' from Mexico, were tested in soils with amended acidity and with 1 to 3 ppm of P. PI 321991, PI 322002, and PI 341307 performed well and have been used in the program as well.

With respect to other species, rye—especially Brazilian landraces growing in acid soils poor in P content and with toxic

Al and Mn levels—performed well. Possibly, a recurrent selection occurred, which allowed the concentration of favorable genes over many generations in the ryes grown in these areas. Triticale cultivars under study showed behavior similar to the best wheats. Barley performed poorly due to its susceptibility to crestamento.

Assessment of uniform material

Soils used at CNPT in screening for tolerance to crestamento or for a more efficient P use are not uniform, which makes it difficult for precise assessment of the material under field conditions. Thus, the material in the F_6 has been assessed in pots in which soil can be placed that has been thoroughly mixed containing toxic levels of Al^{+++} and Mn and at two P levels: O and 120 ppm. The best F_6s were selected based on the production of shoot dry matter at flowering, and compared to the recurrent parents. At the same time, a plot corresponding to each F_6 under test was evaluated in the field and the best populations selected in pots were bulked.

In the following generation, 39 lines selected, along with seven wheat cultivars and one triticale, were assessed under field conditions at two levels of P fertilization: (0 and 80 kg P_2O_5/ha). Three replications of trial were conducted in low fertility soil that had 5 ppm of P, a pH of 4.8, and 2.9 meq Al^{+++}/100 g of soil. Table 7 shows the yields of straw plus grain of 10 lines in decreasing order of plots not receiving P. Table 8 shows grain yields only under the same conditions.

Table 7. Straw plus grain yield of 10 lines and cultivars in a field trial, Passo Fundo, RS, 1986. CNPT/EMBRAPA.

Cultivar/line	Cycle up to maturity	Straw + grain yield without P (kg/ha)	Straw + grain yield with 80 kg P_2O_5 (kg/ha)	Relation of production w/o P/with P (%)	Content of uptaken P (kg/ha) w/o P	Content of uptaken P (kg/ha) with P
Toropi	145	7193 A[b]	8089 A[b]	88.9	9.15	14.39
Minuano	133	6478 B	7638 AB	84.8	8.97	12.23
PF 84741[a]	133	6478 B	7075 B-G	91.5	11.24	12.73
IAC 5-Maringá	133	6096 BCD	7346 BC	83.0	8.64	12.09
PF 84728[a]	133	5895 B-F	6353 J-S	92.8	9.14	10.13
PI 84739[a]	133	5631 C-J	7054 B-G	79.8	8.76	11.33
BH1146	133	5437 E-K	7193 B-F	75.6	8.15	13.22
BR 14 (Thornbird)	127	4978 KL	6388 I-S	77.9	8.00	10.19
CNT 8	133	4712 LM	5943 RS	79.4	6.95	10.44
Triticale BR 1	123	4173 M	6422 I-R	65.0	7.36	11.52
		CV 7.19%	CV 5.36%			

[a] Lines from the Cross BH1146*2/TP.
[b] Duncan Multiple Range Test, 5%.

Using the assessment system described by Fageria and Barbosa Filho (1981), 47 genotypes were classified according to their P use efficiency (considering the total yield of dry matter) as follows:

- Inefficient, nonresponsive (INR): 10.
- Inefficient, responsive (IR): 17, including BH1146, BR 14, CNT 8, and Triticale BR 1.
- Efficient, responsive (ER): 10, including Minuano 82 and IAC 5-Maringá.
- Efficient, nonresponsive (ENR): 10, including Toropi.

Toropi was classified as ENR; BH1146, the recurring line in 35 of the assessed lines was classified as IR, while nine lines from the cross BH1146*2/Toropi were classified as ENR and seven lines from the cross were classified as ER. This demonstrates that breeding was effective in transferring the characteristic.

Comparison of the results in Tables 7 and 8 reveals some interesting contrasts. Toropi, which had the highest straw plus grain yields, had the lowest grain yield. Researchers believe that straw plus grain yields should be an important criterion in parental selection because the excellent capacity for P use in an old cultivar like Toropi (released for cultivation in 1965) can be transferred to a cultivar that is more efficient (higher harvest index) in grain yield.

When considering grain yield only (Table 8), the classification of the material was modified. Toropi becomes INR, Triticale BR 1 switches from INR to ER, and BH 1146, as do most lines, remains the same. The excellent behavior of cultivars IAC 5-Maringá and Minuano 82 should be emphasized. Line PF 84737, which will be studied further, remained efficient and responsive (ER) when considering straw plus grain yields and grain yield only.

Breeding for cultivars that have greater efficiency in P use aims at obtaining germplasm that requires lower

Table 8. Grain yield of 10 lines and cultivars in a field trial, Passo Fundo, RS, 1986. CNPT/EMBRAPA.

Cultivar/line	Yield (kg/ha) Without phosphorus	With 80 kg P_2O_5	Yield relation w/o P/ with P (%)	Yield increase with P_2O_5 (kg/ha)
IAC 5-Maringá	2354 A[a]	2500 B[a]	94.2	146
Minuano 82	2277 AB	2472 B	92.1	195
PF 84741	2257 ABC	2333 B-F	96.7	76
PF 84728	2090 B-E	2152 D-O	97.1	62
Triticale-BR 1	2055 B-F	2930 A	70.1	875
BR 14 (Thombird)	1937 D-K	2437 BC	79.5	500
BH1146	1902 D-K	2368 B-E	80.3	466
PF 84739	1895 E-K	2104 E-Q	90.1	209
CNT 8	1805 F-M	2319 B-G	77.8	514
Toropi	1597 M	1951 L-Q	81.8	354
	CV 8.26%	CV 8.05%		

[a] Duncan Multiple Range Test, 5%.

applications of P fertilizers for a certain yield level. When the results from this trial were studied in economic terms, considering the price of wheat as well as the price of 1 kg of P_2O_5 in Brazil during July 1989, it was found that 674 kg of wheat would be necessary to pay for 80 kg of P_2O_5. Thus, the yield increase of Triticale BR 1, alone, compensates for such an application of P_2O_5. In the remaining treatments, P fertilization at this level would not be economic. PF 84741, which showed a higher absolute result among the lines resulting from BH 1146*2/Toropi cross, outyielded the recurrent parent by 355 kg of grain/ha at 0 kg of P_2O_5, but was inferior to BH1146 by 35 kg/ha in the treatment with 80 kg of P_2O_5. In economic terms based on these results, it would be much more profitable for farmers to plant PF 84741 without P fertilizer.

Considering these promising initial results, a new direction in the breeding work was begun to combine P efficiency with improved yield potential and disease resistance. The first lines resulting from this new phase were assembled in 1989 and are now being evaluated.

Materials with high P efficiency will be most valuable in areas with low yield potential or with unstable yields due to environmental factors such as frost and/or drought. In the first yield assessments carried out in Dourados, Mato Grosso do Sul, under such conditions, lines from the cross BH1146*6/Alondra'S'//BH1146*4/ Toropi, selected for P efficiency and stem rust resistance, were outstanding in 1989 by outyielding the check cultivars BH 1146, BR 20, and IAC 5-Maringá by 103, 51, and 107 %, respectively. A large number of lines from this cross and others, more directed toward more favorable environments, will be assessed in the coming years to confirm the promising initial results.

Characteristics determining greater P efficiency

Experiments have been done to define the characteristics involved in improving P uptake or utilization efficiency of the lines developed in this program.

Research using nutrient solutions—To characterize the Al tolerance of some genotypes selected or bred in the Passo Fundo program, seedlings were placed in nutrient solutions (to study root growth) containing 0, 3, 6, or 10 mg of Al^{+++}/L . Table 9 summarizes some results particularly related to crosses involving BH1146.

It can be seen that BH1146 is more tolerant than Toropi, which already exhibits a high sensitivity to Al^{+++} at 6 mg/ L. BH1146 has no root growth inhibition at 10 mg/L with a constant pH of 4. PG 1, another source used to improve P efficiency, was more Al tolerant than Toropi. Lines from the cross BH1146*2/ Toropi, in general, showed similar or higher tolerance to that of BH1146. In lines from the cross BH1146*6/Alondra'S', PF 839054 showed tolerance similar to the recurrent parent, while the others were less tolerant. These data suggest the invalidity of the hypothesis that the better behavior shown by Toropi in soils with low P availability and high acidity is due to its greater Al tolerance—and perhaps the case for PG 1 as well, in spite of it having shown a greater tolerance to Al^{+++} than Toropi.

The genotypes were studied in nutrient solutions with different P concentrations (0, 0.93, 1.86, 3.72, 7.75, and 15.5 mg P/ L); P extraction and PER were determined after 15 days in these solutions. Reduced PERs in all genotypes (Table 10) are obvious as P concentration is increased. This can be explained by the gradual increase in P content of the tissues as the concentration of the solution increases. For example, with Toropi, the P content in

the dry matter progressed from 0.346% to 0.416, 0.470, 0.500, 0.685, and 0.955%, as P concentration in the solutions increased. The other genotypes behaved similarly.

When comparing PERs across the genotypes, differences in some concentrations are apparent, but there is no clear differentiation. Notwithstanding, considering that one of the genetic mechanisms for Al neutralization is determined by altering soil pH close to the roots, this methodology—in which pH remains constant—may reflect negatively in some of the genotypes that more actively use this mechanism.

Research using homogenized soil

Another hypothesis—that might explain the differences among wheat genotypes as to their capacity in using P—is that certain genotypes can extract "fixed" P

Table 9. Mean root lengths (mm) of wheat cultivars and lines placed in nutrient solutions with four Al concentrations. Campinas, SP, 1987.

Treatment	Al^{+++} concentration (mg/L)			
	0	3	6	10
Toropi	37.2	23.2	11.9	0.0
PG 1	34.6	37.2	16.6	4.8
Minuano 82	43.3	44.2	28.8	14.2
BH1146	40.3	39.0	39.5	7.6
PF 84717 = BH1146*2/TP	57.8	54.0	39.0	13.5
PF 84719 = BH1146*2/TP	57.4	41.3	33.4	27.4
PF 84715 = BH1146*2/TP	61.8	47.5	37.6	17.4
PF 84718 = BH1146*2/TP	52.2	37.3	24.7	10.4
PF 84713 = BH1146*2/TP	42.1	47.0	36.6	17.1
PF 84726 = BH1146*2/TP	35.5	42.2	29.7	18.5
PF 84731 = BH1146*2/TP	37.1	35.6	22.7	8.7
PF 85300 = BH1146*2/TP	43.4	36.4	21.8	4.0
PF 85302 = BH1146*2/TP	28.4	36.8	9.0	14.0
PF 839054 = BH1146*6/ALD'S'	30.5	49.0	31.6	17.9
PF 839074 = BH1146*6/ALD'S'	38.9	39.7	20.3	0.0
GD 8341 = BH1146*6/ALD'S'	16.4	32.3	13.3	0 0

Table 10. PERs of 10 wheat genotypes in various P concentrations in nutrient solution. Campinas, SP, 1987.

P in solution (mg/L)	Toropi	PG 1	Minu-ano 82	BH 1146	PF[a] 84726	PF[a] 84717	PF[a] 84719	PF[a] 84731	GD[b] 8341	PF[b] 839054
0.00	290	254	264	244	291	310	240	278	313	278
0.93	241	240	239	207	266	219	227	228	271	219
1.86	213	180	204	222	232	181	208	169	205	223
3.72	200	213	214	176	195	178	2[illegible]	181	216	192
7.75	146	138	176	173	167	145	184	149	176	176
15.50	105	90	107	110	103	87	96	85	94	110

[a] BH1146*2/TP.
[b] BH1146*6/ALD'S'.

from the soil at the places of exchange or in solution, which would be in a chemically unavailable form to other genotypes. An experiment was conducted in pots using soil mixed thoroughly in a concrete mixer to simulate soil conditions (high acidity, toxic levels of Al^{+++}, and no added P fertilizer) that cause crestamento in plants.

The soil had the following characteristics:

- pH: 4.5.
- Exchangeable Mg: 0.39 me/100 g soil.
- Exchangeable Al: 3.25 me/100 g soil.
- Exchangeable Ca: 1.02 me/100 g soil.
- P: 20.5 ppm.
- K: 148 ppm.
- Organic matter: 3.8%.

Seed from eight cultivars was sown in pots containing 8 kg of soil; the pots were thinned to 11 plants each; this four-replication experiment used no P fertilization. Potash and N were applied basally; one N topdressing was applied.

Shoot and root dry matter and P contents of the tissues were determined in each pot at 45 and 90 days after emergence (Tables 11 and 12).

It should be emphasized that Anahuac 75, one of the cultivars most widely used in Brazil in soils without crestamento problems, was the only cultivar susceptible to these soil conditions—with extremely limited root growth and overall plant development, both at 45 and 90 days. At 45 days, root growth differences were observed among the genotypes (Figure 2a-d), especially Toropi and PF 84737. PF 84737 is derived from the cross BH1146*2/Toropi and the data in Table 11 indicate that it is superior to BH1146 in shoot, root, and total dry weights.

The results obtained at 90 days (Table 12) show differences among the various genotypes, but not as substantial as at 45 days. This can be explained by the limited volume of the soil that could be explored and by the abundant water supply (Foy et al. 1974). In general, the results obtained at 45 days—the excellent behavior of Toropi and the difference between PF 84737 and its recurrent parent BH1146—confirm that breeding had successfully transferred some of the desired traits of Toropi.

Table 11. Shoot, root, and total dry weights at 45 days of eight genotypes grown in pots with acid soil and high Al content, conducted under screenhouse conditions in Passo Fundo, RS, 1987.

	Development at 45 days—Dry weight					
	Roots		Shoots		Total dry weight	
Cultivar	g	%	g	%	g	%
PF 84737	2.275 ab[a]	92	1.7 a[a]	148	3.975 a[a]	110
Toropi	2.475 a	100	1.15 bc	100	3.625 ab	100
Minuano 82	1.85 bc	75	1.275 b	111	3.125 bc	86
IAC 5-Maringá	1.775 c	72	1.225 b	106	3.0 cd	83
BH1146	1.475 c	59	1.025 cd	89	2.5 de	69
PG 1	1.45 c	58	0.9 d	78	2.35 e	65
CNT 8	0.875 d	35	0.65 e	56	1.525 f	42
Anahuac 75	0.2 e	8	0.5 f	43	0.7 g	19

[a] Duncan Multiple Range Test, 5%.

By analyzing the P extracted by various cultivars after 90 days (Table 12), it was found that Toropi was able to extract P, although statistically equal to PF 84737; PG 1 and IAC 5-Maringá were inferior to Toropi and PF 84737. CNT 8, one of the most popular cultivars of farmers in Rio Grande do Sul during the last decade, is inferior to all remaining genotypes—in respect to all of the characters analyzed in this study—except Anahuac 75. This suggests that when there is not specific selection for P efficiency, cultivars that require more P fertilizer will result, thus increasing the cost of the production system. CNT 8 is considered to be moderately tolerant to crestamento.

By analyzing a modified PER index (PERm), where total dry matter produced (in mg) is divided by total P extracted from the tissues, an inverse relationship can be observed between cultivars that are more efficient in dry matter production and P extraction and those that are not. For example, Anahuac 75, which yielded only 3.1% of the dry matter produced by Toropi, showed a PERm of 750 compared to Toropi's PERm of 340 (Table 12). It is very clear that the PERm has no value when cultivars are compared in relation to their capacity to use "fixed" P. Such an inversion occurs possibly as a consequence of relative P availability due to differing root growth between cultivars. Therefore, Toropi can extract more P and, consequently as observed from the nutrient solution studies, there is an increase in P content in the tissues compared to other cultivars that can extract P in lower amounts due to a much smaller uptake surface.

Experiments in volcanic soils without Al toxicity

An attempt was made to study the behavior of some cultivars that have P use efficiency in acid soils in soils having a pH close to neutral, but with severe P limitations. Through collaboration with Ing. Mario Mellado, Quilamapu Experiment Station, a research unit of the Instituto de Investigaciones Agropecuarias, Chile, an experiment was conducted in a "Trumão" soil of the Andes pre-Cordillera, which contained 8 ppm of P (Olsen) and a pH of 6.4. Two levels of P_2O_5 (0 and 200 kg/ha) and one dose of 150 kg of N/ha were applied.

Table 12. Shoot, root, and total dry weights, P extraction, and PER at 90 days of eight genotypes grown in pots with acid soil and high Al content. Passo Fundo, RS, 1987. EMBRAPA/CNPT.

	Development at 90 days				
	Dry matter (g)			Extracted	
Cultivar	Roots	Shoots	Total dry weight	P (mg)	PERm[a]
PF 84737	5.475 b[b]	22.675 a	28.15 a	63.2 ab	445
Toropi	7.0 a	18.425 b	25.425 ab	74.7 a	340
Minuano 82	5.425 b	18.7 b	24.125 abc	55.4 bc	435
IAC 5-Maringá	4.725 bc	18.55 b	23.275 bc	49.3 c	472
BH1146	3.925 c	18.4 b	22.325 bc	53.1 bc	420
PG 1	5.575 b	14.3 c	19.875 c	48.7 c	408
CNT 8	2.075 d	8.475 d	10.55 d	18.6 d	567
Anahuac 75	0.2 e	0.625 e	0.825 e	1.1 e	750

[a] Modified PER index (PERm) = Total dry weight/Total P extracted.
[b] Duncan Multiple Range Test, 5%.

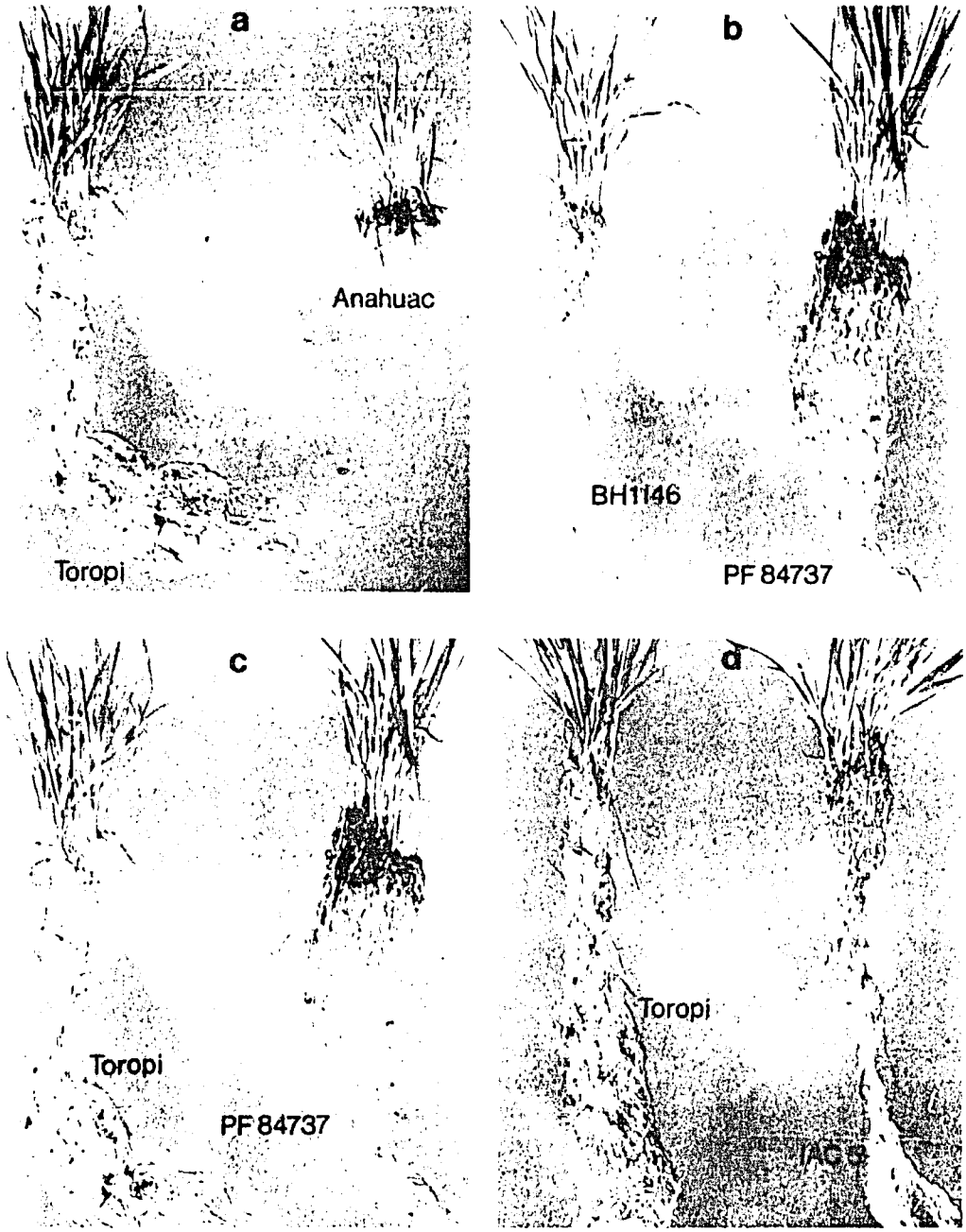

Figure 2. Development of 11 plants of a) Toropi and Anahuac 75, b) BH1146 and PF 84737, c) Toropi and PF 84737, and d) Toropi and IAC 5-Maringá, 45 days after emergence, grown in acid soil with high Al and Mn contents and low P availability. EMBRAPA/CNPT, 1990.

The results (Table 13) showed that Toropi and PG 1 performed well compared to local checks—both in plots without P_2O_5 application and in those receiving 200 kg P_2O_5/ha. Even with the experiment's limitations, the results indicate that the characteristics, which allow certain cultivars to have better P use efficiency in very acid soils, may also function in other soil types that have no Al toxicity and lower acidity.

Effects of mycorrhizae

The results of soil experiments could be confounded by the effects of mycorrhizae, which might alter P uptake. However, the elimination of such effects through soil sterilization could cause additional effects, so all experiments were carried out in the field or in pots using nonsterilized soil.

Nevertheless, in 1985, José Renato Ben (pers. comm.) studied the effects of mycorrhizae in a greenhouse experiment. Using nonsterilized soil and soil sterilized with methyl bromide and two P levels (0 and 120 kg of P_2O_5), he inoculated seeds with mycorrhizae introduced from the Escola Superior de Agricultura Luiz de Queiroz, Piracicaba, São Paulo. Four genotypes were used, two of which had problems of low P content in the seeds. The results (Table 14) show that, in general, the effects of soil sterilization were greater than the effects of the mycorrhizae.

Conclusions

From the research activities conducted at Passo Fundo, the following conclusions can be made.

- There is variability in wheat in relation to P use efficiency—Toropi being one of the cultivars that shows more consistent results for this character.
- The transfer of such a characteristic can be successful in breeding activities through the screening of material under field conditions in areas having low P availability and crestamento and/or selecting material that has more efficiency in areas with higher P levels, but where this element is "fixed".

Table 13. Results from an experiment conducted at Guilamapu Experiment Station, Chile, in volcanic soils with P limitations; average of three replications. 1987.

Cultivars	Yield (kg/ha) w/o P	Yield (kg/ha) with P[a]	Test weight (g) w/o P	Test weight (g) with P[a]	Plant height (cm) w/o P	Plant height (cm) with P[a]
Lancero[b]	2250	3400	81.1	81.2	75	80
Cisne[c]	1580	2310	82.7	83.7	90	95
Nabo[c]	1050	1390	78.4	80.8	75	85
Nobre	1010	1350	79.3	80.2	110	115
PG-1	2240	2690	80.2	81.4	135	140
Toropi	2210	2770	81.2	82.1	135	140
Triticale BR 1	960	1150	76.3	78.6	90	100

[a] 200 kg P_2O_5.
[b] Chilean check with facultative growth habit.
[c] Chilean check with spring growth habit.

- The trait for greater P efficiency shown by Toropi appears due to its larger root system in acid soils with high Al contents, which allows it to use P that apparently would be unavailable to other genotypes. This characteristic can be transferred to other genotypes.

- The screening system employed can be easily used in other breeding programs that work with soils having problems similar to those in Passo Fundo.

- The genotypes that are more efficient in acid soils are also efficient in volcanic soils with a pH close to neutral and without toxic Al.

- There will be a greater success involving breeding efforts for areas with P deficiency and crestamento problems if, in addition to screening for Al and Mn tolerance, P use efficiency is also taken into consideration.

- The variability in P uptake efficiency and/or use in wheat may lead to specific cultivar recommendations for farmers that will result in a more profitable return from P fertilization, especially in regions where farmers' profit margins are very narrow.

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Table 14. Dry matter production of shoots (g/pot) of different wheat genotypes obtained in soil with and without P, with and without sterilization, and with (C/M) and without (S/M) mycorrhizae inoculation of the seed. Passo Fundo, RS, 1985. CNPT/ EMBRAPA.

P_2O_5 doses ppm	Genotypes				
	Toropi	BH1146	BH1146*2/TP line 20	BH1146*2/TP line 26	Mean
Nonsterilized soil					
0 S/M	0.54	0.61	0.18[a]	0.24[a]	0.39
C/M	0.69	0.53	0.25	0.22	0.42
120 S/M	7.6	4.5	3.2	2.7	4.5
C/M	8.1	5.1	3.8	4.2	5.3
Sterilized soil					
0 S/M	1.22	0.93	0.46	0.55	0.79
C/M	1.05	0.70	0.38	0.34	0.62
120 S/M	8.9	5.8	5.0	4.6	6.1
C/M	8.9	4.8	4.6	5.6	6.0

[a] Seed with low P content.

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Resumen

En las investigaciones brasileñas se han logrado grandes respuestas en el rendimiento de trigo a la fertilización con fósforo (P). Sin embargo, en suelos ácidos con altos contenidos de aluminio y manganeso, las plantas no pueden aprovechar una proporción considerable del P aplicado. El Instituto Agronómico de Campinas (IAC) y el Centro Nacional de Investigación de Trigo (CNPT) mejoran variedades de trigo para lograr un uso más eficiente del P. Como resultado de los trabajos con el nutrimento en soluciones y suelos, es posible caracterizar las variedades de trigo según las distintas respuestas vinculadas con esta característica. Los ensayos realizados en soluciones del nutrimento permiten diferenciar en 15 días las variedades eficientes de las no eficientes en el aprovechamiento del P. El programa fitotécnico efectuado en el campo ha tenido éxito en transferir la característica de la eficiencia en el uso del P de la variedad brasileña Toropi a líneas adaptadas a otras regiones de producción. Se ha comprobado que la característica de una mayor absorción de P encontrada en Toropi es resultado de su sistema radical más grande que, en suelos ácidos con un alto contenido de aluminio, le permite explorar una porción mayor del suelo y utilizar el P que, aparentemente, no está disponible para otros genotipos.

The Role of Mycorrhizal Fungi in Crop Nutrition in the Warmer Regions

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Abstract

Agricultural scientists are recognizing more and more the beneficial effect of vesicular-arbuscular mycorrhizal (VAM) fungi on crop development. The main advantage of mycorrhizal fungi is their ability to promote phosphorus uptake by crops—in particular under marginal soil conditions with environmental extremes and low nutrient status. Many factors can decisively influence the development of VAM fungi. In this report, the crucial role of the mycorrhizal symbiosis in crop nutrition under various environmental conditions, agronomic practices, and plant breeding aspects is presented and discussed. Considering the potential that VAM fungi offers, the scale of mycorrhizae research in tropical countries should be substantially expanded in order to assure an effective application of this symbiosis in cropping systems of the warmer regions.

Introduction

In many parts of the warmer regions of the tropics and subtropics, restoration and maintenance of soil fertility are basic and critical environmental problems. Most soils in these regions are characterized by a low nutrient status and high phosphorus sorption capacity. Since phosphorus is emerging as the element that is most limiting to crop growth, the application of phosphate fertilizers becomes indispensable to obtain adequate yields. In view of the rising prices of P fertilizers on the world market, many farmers with only limited financial resources have tended to apply less phosphate, and in many tropical countries the application of P fertilizers is not even a common practice. Consequently, anticipated crop yields are not attained, which leads, in combination with demographic pressure, to an increasing use of fragile marginal land. This can cause long-term, sometimes irreversible, environmental damage caused by soil degradation and erosion.

To alleviate this situation, different agricultural practices are being tested in national and international research centers with the aim of improving the efficiency of applied P fertilizers regarding:

- Determination of the best P fertilizer rates and placement methods.
- Introduction of legumes into crop rotation.
- Application of lime to minimize phosphorus fixation.
- Evaluation of local, inexpensive P sources (rock phosphate).

In this context, agricultural scientists are becoming more widely appreciative of the important role of vesicular-arbuscular mycorrhizal (VAM) fungi in crop nutrition.

The occurrence of VAM fungi are among the most widespread of all symbiotic associations in higher plants. This association is characterized by a mutual dependence. While the host plant provides the fungus with photosynthates, the main contribution of the latter is enhancing phosphorus uptake from a greater soil

volume by extraradical hyphae. This growth-promoting ability of VAM fungi by improved P availability has attracted many agricultural scientists; research with a wide range of crops has been the subject of intensive study (Daft and Nicolson 1969, Bethlenfalvay et al. 1982, Abbott et al. 1983, Diederichs 1990).

This report aims to demonstrate the crucial role of the mycorrhizal symbiosis in crop nutrition and to stimulate further urgently needed practical research activities that are necessary for an effective application of this symbiosis in cropping systems of the warmer regions.

Morphological Features of VAM Fungi

To understand the mechanism of the mycorrhizal symbiosis, some description of the VAM fungi's morphological features is indispensable. VAM fungi, which belong to the Endogonaceae, a family in the Mucorales, are ubiquitous soil inhabitants. They are obligate symbionts and cannot grow and reproduce in the absence of a host plant. Most plant families excluding Cruciferae, Chenopodiaceae, Cyperaceae, and a few others are mycorrhizal. However, their dependence on VAM fungi is rather variable as recent studies have demonstrated.

The life cycle of the fungi develops as follows:

- Hyphae penetrate into the primary cortex of the root followed by intercellular spread.
- Arbuscules (hyphal branches) in root cells are presumed to have special significance in the bi-directional transfer processes of nutrients between the fungus and the host plant.
- Vesicles (inter- or intracellular sack-like swellings at the tip of a hypha) contain lipid droplets and are obviously storage organs of the fungus.
- Spores (mostly outside the root), considered to be reproductive organs, are able to survive for many months in dry soils. Spore morphology is used mostly for taxonomic identification.

One of the most important parts of the mycorrhizal system, however, is the external mycelium (hypha), which allows the root system to explore a much greater soil volume. These hyphae reach sources of phosphate and other immobile nutrients, which would otherwise be inaccessible to the root system of the plant and consequently unavailable for plant development.

Materials and Methods

The experiments presented in this paper were conducted under greenhouse conditions at the Institute of Agronomy in the Tropics (IAT), Göttingen, Germany, and at the Cerrados Agricultural Research Center (CPAC), Planaltina, Brazil.

The soil used at IAT was an acid forest soil (pH 3.8) mixed with quartz sand at a ratio of 1:1 (w/w) containing very little available P. According to the arrangement of the experiments, the original soil pH was adjusted to 4.5, 5.5, and 6.5 by adding adequate amounts of $CaCO_3$. The soil mixture was steamed at 90°C for 2 hours and then air-dried. In addition to a basic fertilization with N, K, and Mg, P was supplied at a rate of 90 kg P/ha as soluble monobasic calcium phosphate, $Ca(H_2PO_4)_2 \cdot H_2O$ (MCP); hydroxylapatite, $Ca_5(PO_4)_3OH$ (HA); or as natural rock phosphate originating from different countries. In some experiments, there was also a treatment without additional P fertilization or with ferric phosphate ($FePO_4$). Various soil temperatures (20, 25,

30, and 35°C) were maintained by keeping pots in water baths regulated by thermostats. For mycorrhizal inoculation, the seedling roots were dipped into a suspension of infected root fragments of an appropriate host plant before being transplanted into the pots.

The experiments at CPAC were carried out in an unsterilized virgin dark red latosol (Typic Haplustox, U.S. system of soil taxonomy), which had the following properties: pH (KCl), 4.0; organic C, 2.2%; extractable P (Bray I), 1.8 mg P/kg; exchangeable cations (meq/100 g soil): Al (1.3), Ca (0.3), Mg (0.15), K (0.11); Al saturation, 68%; free Fe_2O_3, 11%. According to local agricultural practices, the original soil pH was adjusted to 5.7 using dolomitic lime and a basic fertilization was applied at the following rates: 60 kg N/ha (NH_4NO_3), 50 kg K/ha (KCl), and 40 kg/ha of a fritted trace element mixture (BR12, from Brazil). For the phosphorus treatment, two commonly used P sources were applied: soluble single superphosphate (total P, 8%), and a low grade rock phosphate (Patos de Minas) from Brazil (total P, 10.7%). The mycorrhizal inoculum, an air-dried mixture of soil/roots/spores consisted of naturally occurring VAM fungi and was applied at the rate of 2 g/pot.

The experiments were arranged in a randomized complete-block design. All mycorrhizal treatments (M) were tested against uninoculated plants in unsterilized soil (NI) or uninoculated plants in sterilized soil (NM). Plants were harvested after 2-3 months according to their growth cycle; shoot dry weights were recorded. After clearing and staining the roots with trypan-blue (Phillips and Hayman 1970), mycorrhizal infection intensity and root length were determined using the grid line intersect method (Giovannetti and Mosse 1980). Total infected root length was calculated by multiplying the infection intensity by the root length.

Results and Discussion

Of the many factors that can decisively influence the development and efficiency of VAM, environmental conditions (soil temperature, light intensity, water availability, soil aeration, soil pH, and toxicity of aluminum and manganese) deserve special attention. However, agronomic practices (phosphate fertilizer application, liming, and crop rotation with legumes), which can substantially alter soil conditions, are of equal importance. One of the most significant aspects of the ecology of VAM fungi is the interaction with other microorganisms at the rhizoplane and in the endorhizosphere (e.g., with N_2 fixing bacteria). Root pathogens should also be considered when evaluating the potential of VAM fungi. In this report, some of the research findings related to a number of the above mentioned factors are discussed. As these investigations dealt with cropping systems in the tropics, the following research findings will not be exclusively related to wheat. Nevertheless, the present results may serve as an indication demonstrating the potential of VAM fungi for agricultural systems in the warmer regions.

Ecologic factors

Drought stress—Crop production in semi-arid and subhumid regions is mostly limited by insufficient availability of water, unless expensive irrigation systems are implemented. The positive influence of mycorrhizal fungi in improving the water relations of host plants during periods of moisture shortages has been reported (Nelson and Safir 1982, Allen and Bossalis 1983, Busse and Ellis 1985, Ellis et al. 1985, Simpson and Daft 1990). Sieverding (1981) revealed that even relatively drought tolerant crops such as *Sorghum bicolor* can benefit from a symbiotic association with VAM fungi (Table 1).

With MCP fertilization, water consumption of NI and M plants showed only small differences under all three water regimes. But with less soluble HA, considerably less water was consumed by mycorrhizal plants in the lower water regimes (50% and 10% of field capacity), thus economizing water by 43.7% and 26%, respectively. This result can be explained by an improved P uptake of mycorrhizal plants under restricted P conditions resulting in increased plant growth that resulted from a better utilization of water (Sieverding 1981). Although the present experiment does not give indications of an improved water uptake by mycorrhizal plants, this important aspect should not be neglected. Bethlenfalvay and Ames (1987) reported that water stress increased the size of the external mycelium of *Glomus mosseae*, thus it can be assumed that an external mycelium exploring a greater soil volume could promote water uptake, especially if considering the results of Hardie (1985), who showed that the external mycelia of VA mycorrhizae are significantly involved in water uptake, since their reduction affected plant water relations. The fact that VAM fungi improve the water use efficiency is an important aspect for rainfed crops under semi-arid conditions where deficient soil moisture often limits the amount of fertilizers that can be applied.

Soil temperature—Physiological activities of plants and soil microorganisms depend on optimum soil temperatures and many reports have demonstrated that mycorrhizal efficiency can also be strongly influenced by different soil temperatures (Furlan and Fortin 1973, Schenk and Schröder 1974, Nyabyenda 1977, Diederichs 1981, Saif 1981, Sieverding 1988).

The effect of *Glomus manihotis* on growth of *Triticum aestivum* cv. Ralle fertilized with different P sources was tested using four soil temperatures (Fabig et al. 1989). Significant increases in shoot dry weight by *G. manihotis* were found with Florida-Pebble and Khouribga rock phosphates up to a soil temperature of 30°C, but with MCP no growth response due to inoculation was observed (Figure 1). The low solubility of Kola rock phosphate resulted in lower yields compared with the other rock phosphates and *G. manihotis* proved to be effective only at 20 and 25°C. In the treatments with rock phosphate, mycorrhizae increased P uptake in the shoots significantly at all soil temperatures being most pronounced at 20°C. At 35°C P uptake was low, even in the treatment with MCP. Corresponding with the known temperature requirements of wheat, the highest efficiency of *G. manihotis* was found at 20°C. Comparable results also with wheat have been reported by Hetrick et al. (1984). This, however, cannot be regarded as generally valid. According to these authors, mycorrhizal efficiency is

Table 1. The effects of phosphorus source (monobasic calcium phosphate, MCP, or hydroxylapatite, HA) and mycorrhizal association (nonmycorrhizal, NM; or mycorrhizae inoculated, M) on water consumption (ml H_2O consumed per 1 g shoot dry matter) of *Sorghum bicolor*.

Treatments		Water consumption	
Fertilizer	Water regime (% field capacity)	NM	M
MCP	90	406	416
	50	406	415
	10	433	453
		LSD 5% 16	
HA	90	905	814
	50	1722	970
	10	1699	1259
		LSD 5% 133	

Source: Sieverding (1981).

best at 25-30°C. Considering the results of Sieverding (1988), it seems that *G. manihotis* is rather an exception since this fungus, originating from a warm climate, proved to be effective at low soil temperatures as well. Agronomic practices in the warmer regions should be formulated to optimize soil temperatures to guarantee maximum advantage from the vesicular-arbuscular mycorrhizal symbiosis.

Agronomic practices

Liming—The soil reaction (pH) has a profound influence on many factors that determine the suitability of a soil for crop growth, including soilborne microorganisms. While semi-arid soils are often excessively alkaline, soils of tropical regions with high rainfall are mostly acidic. In both regions, undesirable effects—such as reduced solubility and reduced availability of phosphates and minor elements or toxic effects on the root system—can substantially impede crop production. On acidic tropical soils, liming often overcomes stress conditions. However, inappropriate lime application may induce chemical problems and also inhibit desirable activities of microorganisms adapted to the local soil properties. In this context the efficiency of the VAM fungus *G. manihotis* was tested at different soil pHs using *Sorghum bicolor* as the host plant fertilized with different phosphates (Figure 2).

Glomus manihotis greatly improved shoot dry weight at the lower pH levels—being most pronounced with the Florida-Pebble and Khouribga rock phosphates, which produced shoot growth comparable to MCP. With Kola rock phosphate, the effect of mycorrhizae was much smaller probably due to its lower solubility. These

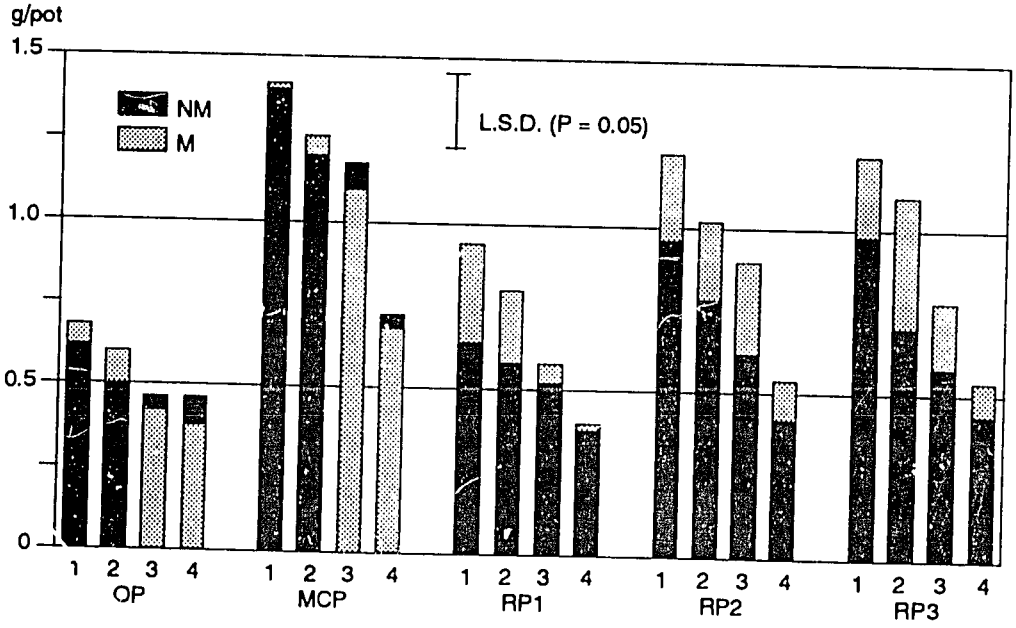


Figure 1. Shoot dry weight of nonmycorrhizal (NM) and mycorrhizal (M = *Glomus manihotis*) *Triticum aestivum* at four temperature levels (1 = 20, 2 = 25, 3 = 30, 4 = 35°C) and different phosphate treatments (OP = without phosphate, MCP = monobasic calcium phosphate, RP1 = Kola, RP2 = Florida-Pebble, RP3 = Khouribga). Source: Fabig et al. (1989).

results are in agreement with the findings of Hayman and Tavares (1985), indicating that the beneficial effect of *G. manihotis* is greater at lower soil pH. Fabig et al. (1989) reported a similar tendency with *Glomus macrocarpum*. This, however, is in contrast with the results of Graw (1978), who obtained enhanced efficiency of *G. macrocarpum* only at higher soil pH. Diederichs (1978) also demonstrated that the development of *G. macrocarpum* in the roots of wheat was promoted by higher soil pH. From these results it must be concluded that VAM fungi differ in their reaction to soil pH. Consequently, agricultural practices that could modify soil pH should be thoroughly evaluated with regard to their effect on the mycorrhizal population; otherwise the beneficial effect of mycorrhizae on the phosphorus nutrition of crops may be reduced.

P fertilization—Maintenance of soil fertility is essential to farming with sustained or enhanced yields. Many soils in the warmer regions, however, are inherently deficient in the available nutrients needed for economic yields, particularly in phosphorus. Thus, fertilizer application becomes indispensable to guarantee the maintenance or enhancement of yields. Sanchez (1976) presented evidence that, on large areas of acidic tropical soils, some rock phosphates—or other phosphates less processed than superphosphate—are nearly or as effective as the considerably more costly superphosphate. Considering recent research, it can be concluded that VAM fungi decisively contribute to enhancing the availability of applied phosphorus fertilizers.

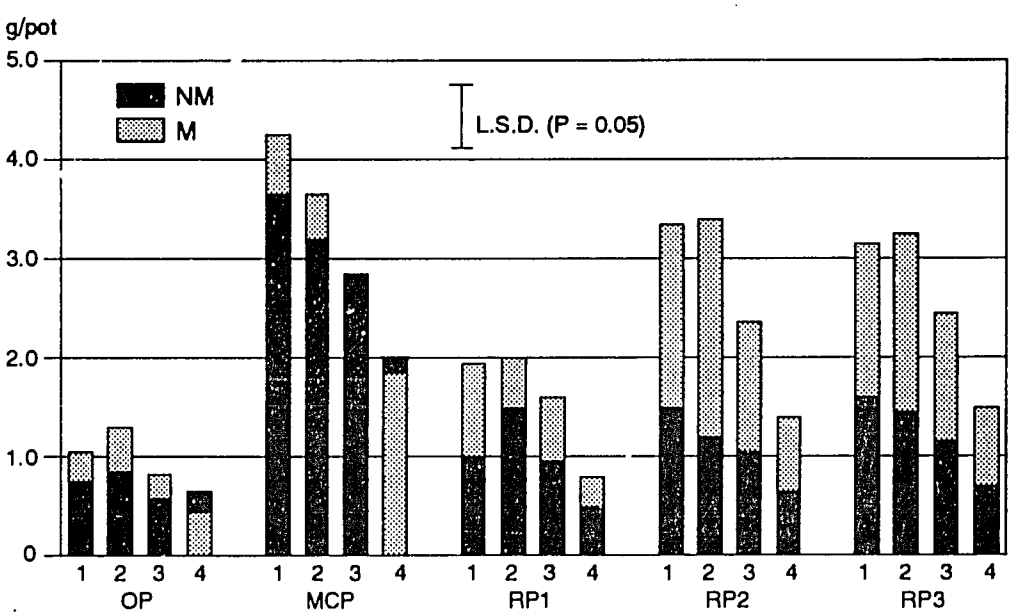


Figure 2. Shoot dry weight of nonmycorrhizal (NM) and mycorrhizal (M = *Glomus manihotis*) *Sorghum bicolor* at four pH levels (1 = pH 4.5, 2 = pH 5.5, 3 = pH 6.5, 4 = pH 7.5) and different phosphate treatments (OP = without phosphate, MCP = monobasic calcium phosphate, RP1 = Kola, RP2 = Florida-Pebble, RP3 = Khouribga). Source: Fabig et al. (1989).

A research study was carried out at the EMBRAPA/CPAC Research Station to verify the influence of different P sources on the efficiency of several tropical VAM fungi on growth of maize, *Zea mays* (L.) cv. Cargill 111. The fungi had previously been introduced into a virgin dark Latosol.

The introduction of additional VAM fungi markedly affected plant growth response of *Z. mays* (Figure 3). In most cases, a beneficial effect of the introduced VAM fungi was recorded. Some differences between the P sources were detected and four classes could be distinguished:

- M_2, *Gigaspora gigantea*; M_4, *Scutellospora reticulata*; M_5, *Scutellospora gilmorei*; and M_7, *Glomus manihotis* proved to be efficient only in the presence of rock phosphate.

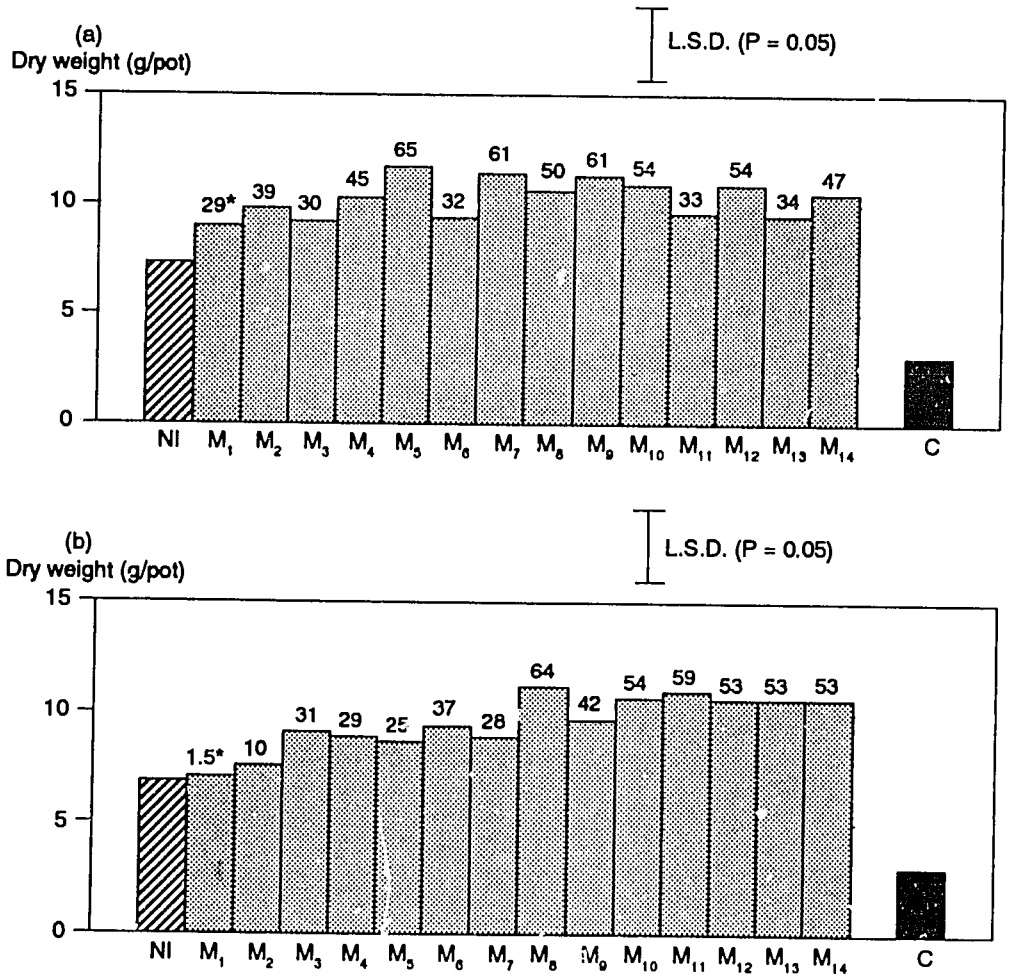


Figure 3. Shoot dry weight (g/pot) of *Zea mays* inoculated with 14 VAM fungi and fertilized with (a) rock phosphate or (b) single superphosphate. NI = noninoculated plants. C = control, plants not inoculated and not fertilized with phosphorus. *Increase (%) when compared to NI plants. Source: Diederichs (1985).

- M_{11}, *Entrophospora colombiana*, and M_{13}, *Glomus pallidum*, improved plant growth only with single superphosphate.

- M_{12}, *Acaulospora scrobiculata*, promoted plant growth in both P treatments, although it was more effective with rock phosphate.

- M_8, *Glomus albidum*, was also beneficial with both P sources, but highest efficiency was observed with single superphosphate.

Similar results, indicating that the ability to mobilize phosphorus from different P sources varies with VAM fungal species, were also obtained with sorghum, soybean, and pearl millet (Miranda 1982, ICRISAT 1984). For agricultural practices, however, it should be kept in mind that considerable differences between the host plants have been observed when using the same VAM fungal cultures. Diederichs (1985, 1990) found that M_1 and M_3, which did not enhance plant growth of *Z. mays*, significantly improved shoot dry weights of *Cajanus cajan* under the same soil and nutritional conditions. A specificity of certain VAM fungi for the P source and for the host must be assumed (Graw 1979).

The infection intensity of *Z. mays* plants inoculated with 14 VAM fungi was higher in the treatment with single superphosphate than with rock phosphate (Table 2). Reports in the literature differ from these data and thus the response may not be a general phenomenon.

Some researchers (Daft and Nicolson 1969 and Hetrick et al. 1984), who also worked with maize, obtained results indicating that increasing P levels markedly depressed root infection. On the other hand, Abbott and Robson (1977), Mosse and Phillips (1971), and Porter (1978) reported an increase in percentage of infection when small amounts of P were added to a P-deficient soil. The latter concluded from field experiments that moderate to high applications of superphosphate do not affect the infectivity nor the effectiveness of a VAM population of a pasture soil in western Australia.

These partly contradictory results emphasize that the interaction VAM infection/P application with regard to plant development is rather complex, especially under tropical soil conditions. The often used term "P-deficient soil" should be considered as rather relative, depending on specific characteristics such as the P requirement of the host plant, the P sorption of the soil, the degree of immobilization of applied phosphorus,

Table 2. The effect of phosphorus fertilizer source on the mycorrhizal infection intensity of *Zea mays*, inoculated with 14 VAM fungi.

Inoculation	P source: Rock phosphate	P source: Super-phosphate
NI	0.83	0.90
M_1	0.93	1.09
M_2	0.83	1.17
M_3	0.85	1.12
M_4	0.83	1.18
M_5	0.87	1.08
M_6	0.90	1.10
M_7	1.06	1.13
M_8	0.96	1.02
M_9	1.01	1.01
M_{10}	1.09	1.25
M_{11}	1.04	1.12
M_{12}	0.95	1.11
M_{13}	0.94	1.16
M_{14}	0.95	1.14
Control (NI, no P)	0.92	0.92
LSD (P=0.05)	0.13	0.19

Source: Diederichs (1985).

and the agricultural practices used to improve P availability. All these factors differ under the various tropical soil conditions and, consequently, VAM effectiveness and infection will vary.

Interaction between VAM fungi and N_2 fixing rhizobia

Nitrogen fixation by legumes can be an effective economic way of providing N to subsequent crops. However, nutritional factors such as phosphorus deficiency may seriously affect the legume-rhizobium symbiosis. In this context, investigations were carried out to verify to what extent various indigenous VAM fungi of the Cerrado ecosystem could improve plant growth of *Cajanus cajan* (L.) Millsp. fertilized with two locally common P sources of different solubility and inoculated with rhizobium belonging to the cowpea type.

Using "Patos de Minas", a low grade rock phosphate, all VAM fungi greatly enhanced shoot dry weight of *C. cajan* (Figure 4) as a result of improved P uptake due to mycorrhizal inoculation. With superphosphate, however, shoot dry weights of NI and M plants were always equal. Comparable results were also obtained by Manjunath and Bagyaraj (1984) and Ames and Bethlenfalway (1987). The positive influence of the tested fungi on nodule formation was well documented in the rock phosphate treatment (Table 3). All mycorrhizal fungi mobilized phosphorus from sparingly soluble rock phosphate not otherwise available for plant development or for nodule formation. With superphosphate, none of the VAM inoculation treatments had an influence on nodulation. The effect of P stress severely inhibited nodulation in the treatment without P fertilization, and when plants were fertilized with rock phosphate and not inoculated with VAM. It is apparent from this study that leguminous crop plants can derive a double benefit from a combined inoculation with effective VAM strains and rhizobia especially under phosphorus limiting conditions (Figure 5). This is an important aspect especially with regard to the introduction of legumes as green manure into crop rotations for building up soil fertility. In this context the results of Reid et al. (1987) should be emphasized. Under field conditions, they found a significantly greater VAM infection in maize roots when either soybean or *Mucuna aterrima* were used previously as

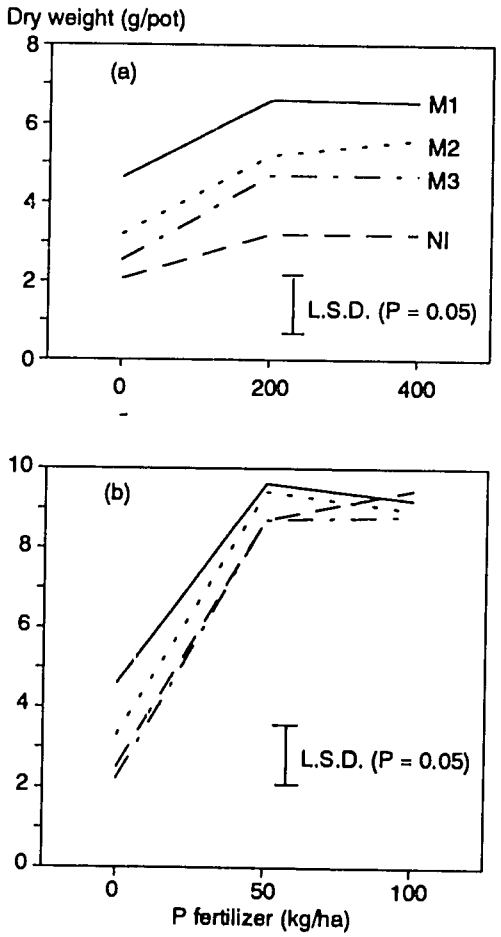


Figure 4. Shoot dry weight (g/pot) of *Cajanus cajan* plants inoculated with three mycorrhizal fungi and fertilized with different levels of (a) rock phosphate and (b) superphosphate. Source: Diederichs (1990).

a green manure. Sieverding and Leihner (1984) reported similar results with cassava.

Interaction between *Azospirillum* spp. and VAM on wheat

As presented above, tripartite symbiosis is common in the leguminous crops that provides a significant contribution to the growth of the host. Multisymbiosis among cereal plants and microorganisms capable of fixing nitrogen or absorbing phosphorus from the soil may be a substantial contribution to plant nutrition, in particular for environments in which nitrogen and phosphorus sources are both limited. There are many reports that associative bacteria of the genus *Azospirillum* can promote growth of gramineae (Döbereiner 1983). Relatively little research has been done on the combined inoculation of VAM and *Azospirillum*. In a recent study, emphasis was placed on the effect of the timing of the inoculation with *Azospirillum brasilense* on VAM (*Glomus macrocarpum*) with *Triticum aestivum* L. cv. "Ralle".

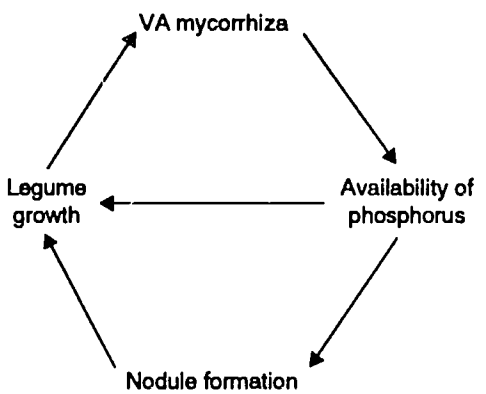


Figure 5. Schematic presentation of the role of VA mycorrhizae in improving availability of phosphorus, nodule formation, and growth of legumes. Source: Diederichs (1990).

The shoot dry weight of wheat was improved due to the inoculation with VAM fungi by 20% in comparison to the uninoculated control, whereas the inoculation with *A. brasilense* alone was only effective at 2 weeks after planting (Table 4). However, the highest yield responses were obtained with a dual inoculation, i.e., with VAM and with *A. brasilense* at 1 or 2 weeks after planting. These results agree well with Barea et al. (1983) and Buwalda et al. (1985). It appears that inoculation at 2 weeks after planting enhanced shoot dry weight due to increased P and N uptake (Wanisch 1989). A synergistic effect of VAM fungi and *A. brasilense* on *Sorghum bicolor* and *Pennisetum americanum* was reported when both microorganisms had been added simultaneously at planting (Pacovsky et al. 1985, Rao et al. 1985). However, in the study reported, shoot dry

Table 3. Number of nodules (number/pot) in *Cajanus cajan* as influenced by three mycorrhizal fungi and different levels of phosphate from two P sources.

	Superphosphate kg P/ha			Rock phosphate kg P/ha		
Inoculation	0	50	100	0	200	400
Not inoculated	4	50	73	4	7	10
Gigaspora margarita	20	46	73	20	53	41
Scutellospora verrucosa	7	68	56	7	29	40
Acaulospora rehmii	9	46	52	9	22	46
LSD (P = 0.05)		22			23	

Source: Diederichs (1990).

weight was impaired in the combined inoculation treatment at planting time suggesting that *Azospirillum* and VAM fungi compete for the same source of carbohydrate; but data at 1 and 2 weeks after planting reveal that competition for carbohydrates may not occur after establishment of the VAM symbiosis.

Table 4. Shoot dry weight (g/pot) of *Triticum aestivum* without/with *Glomus macrocarpum* and inoculated with *Azospirillum brasiliensis* at planting (t_0), at 1 week after planting (t_1), and at 2 weeks after planting (t_2).

Inoculation-Treatment	Time of Azospirillum inoculation t_0	t_1	t_2
Not inoculated (absolute control)	1.70a		
VAM	2.04bcd		
A. brasilense	1.74a	1.76a	1.97bc
VAM + *A. brasilense*	1.90ab	2.15cd	2.21d

Data followed by the same letter are not statistically different at P = 0.05 (DMRT).

Source: Wanisch (1989).

Interaction between mycorrhizal fungi and root pathogens

The interaction between VAM and nematodes has attracted the attention of agricultural scientists during the last decade. Some reports demonstrate suppressed nematode reproduction, improved plant vigor, and a decrease in disease severity following inoculation with VAM fungi (Kellam and Schenk 1980, Suresh and Bagyararaj 1984, Ingham 1988).

In the Cerrado region of Brazil, many cultivated plant species (maize, beans, soybeans, cassava, and upland rice) are infested with nematode species, especially *Meloidogyne javanica* (Sharma 1979). The following research investigated whether native VAM fungi differ in their ability to reduce the effect of *M. javanica* on chickpea (*Cicer arietinum* L.), a legume crop that has demonstrated great potential for that region. Of the five mycorrhizal strains tested (*Gigaspora margarita*, M_1; *Gigaspora* sp., M_2; *Gigaspora gigantea*, M_3; *Glomus manihotis*, M_4; *Entrophospora colombiana*, M_5), M_1, M_2, and M_4 significantly suppressed the parasitic effect (galls) and the production of larvae (Table 5). However, shoot dry weight (Figure 6) and root fresh weight (Table 5)

Table 5. Root fresh weight of *Cicer arietinum* (g/pot), galls/g of root, egg masses/g of root, eggs/g of root, and larvae in 50 g of soil. The absolute values (x) were transformed into $(x + 0.5)^{0.5}$.

Inoculation	Root fresh weight	Galls/ g of root	Egg masses/ g of root	Eggs/ g of root	Larvae in 50 g of soil
NM	3.2	6.9	4.9	55.5	12.5
M_1	12.4	3.6	1.8	26.7	6.6
M_2	5.7	3.7	2.0	22.9	7.0
M_3	2.9	3.7	2.1	19.5	12.9
M_4	11.2	2.1	1.3	16.1	4.1
M_5	3.7	5.6	3.3	53.6	8.6
LSD (P = 0.05)	4.2	2.7	2.1	23.1	5.4

Source: Diederichs (1987).

of nematode-infested chickpea plants were significantly improved only with M_1 and M_4. Similar results with other endophytes were also obtained by other research workers (Rancadori and Hussey 1977, Strobel et al. 1982, Sitaramaiah and Sikora 1982). The infestation with nematodes reduced the infection intensity of the growth-stimulating mycorrhizal fungi, except M_1 (Table 6). This result, however, cannot be regarded as generally valid. Partly contradictory observations indicate that nematodes were capable of stimulating as well as reducing the mycorrhizal infection intensity, while plant growth profited from the mycorrhizal symbiosis (Bagyaray et al. 1979, Kellam and Schenk 1980). Mycorrhiza-induced growth improvement of nematode-infested plants is obviously a result of fungi that do not lose their effectiveness in the presence of nematodes and that also inhibit nematode reproduction. Although the biochemical mechanisms involved in this interrelationship are still unknown, further research efforts on the practical aspects appear rewarding—especially with regard to biological pest control.

Table 6. Infection intensity (arcsin transformed) of chickpea plants inoculated with five VAM fungi, without and with nematodes.

Inoculation	Without nematodes	With nematodes
NM	0.00	0.00
M_1	0.92	0.92
M_2	0.82	0.33
M_3	0.81	0.27
M_4	1.13	0.79
M_5	1.15	0.29
LSD (P = 0.05)	0.13	0.14

Source: Diederichs (1987).

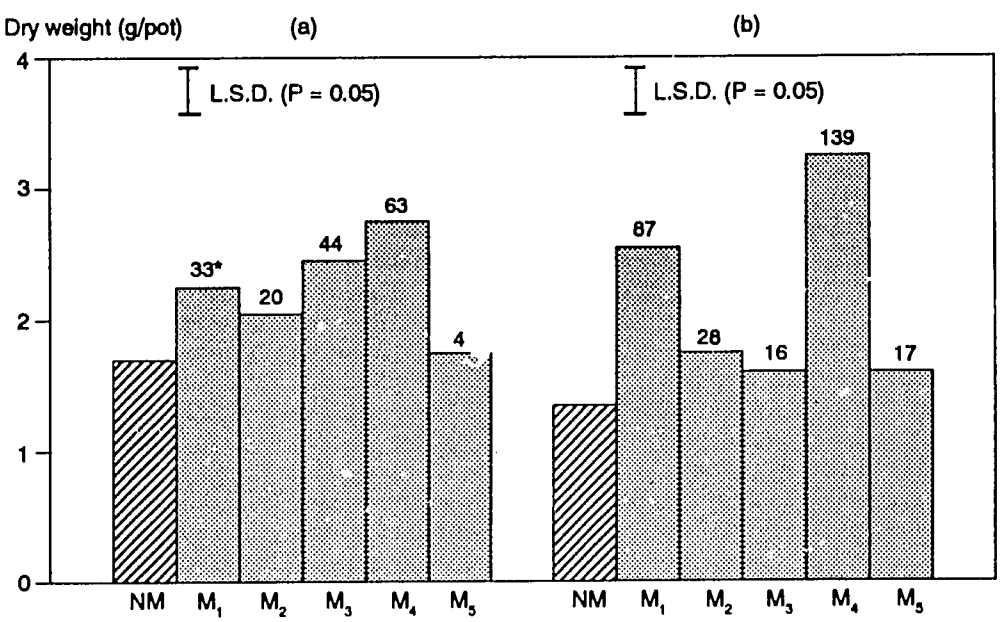


Figure 6. Shoot dry weight (g/pot) of *Cicer arietinum* without (a) and with (b) nematodes inoculated with five VAM fungi. *Increase (%) when compared to noninoculated plants (NI). Source: Diederichs (1987).

Genetic aspects of vesicular-arbuscular mycorrhizae in wheat
Mycorrhizal colonization and growth response to VAM inoculation is host-dependent and heritable. Screening experiments have shown a high genotypic variability in VAM infection and efficiency within several plant species (Bertheau et al. 1980, Jensen 1985, Krishna and Williams 1987, Krishna and Lee 1987, Mercy et al. 1990).

Results of a project involving spring wheat—Manske (1989) reported on an intensive research project at IAT concerning genetic aspects of VAM with spring wheat. In one experiment, 44 spring wheat genotypes—22 high yielding varieties (HYVs) and 22 old varieties, landraces, and wild forms (LRs)—were screened for colonization and growth response to inoculation with the VAM fungus *Glomus manihotis*, a very efficient strain. In a second experiment, the high VAM efficiency of an old variety could be transferred by reciprocal crossing to a less efficient HYV. The plants were grown under greenhouse conditions, two plants per pot with 1 kg soil. They were harvested at the milk-ripe stage of the grains. The growth of the inoculated plants (M) was compared with that of uninoculated controls (NM). VA mycorrhizal efficiency was defined as the degree to which a genotype yields better with than without VAM (M/NM in %).

The wheat plants in the screening were fertilized with iron phosphate ($FePO_4$), which produced an extreme P deficiency so that the wheat plants remained small and did not tiller. All 44 wheat varieties were infected by the VAM fungus *G. manihotis* and their yields were increased by the inoculation, especially with LRs. The majority of the primitive wheats (LRs) ranged in their VAM efficiency of ear dry weight above 130%, 20% more than the mean of HYVs (Figure 7).

The symbiosis increased the ear more than the shoot dry weight. The haulm length of most of the HYVs was shorter than that of the LRs. Root length of the infected plants was positively correlated with shoot dry weight (correlation coefficient, r=0.49), haulm length (r=0.47), and shoot P uptake (r=0.55).

LRs produced greater root length than HYVs on the average. HYVs showed less variation in root length and plant height than LRs. With their more intense root systems, many of the LRs showed greater infected root length than HYVs.

An intense root system and high mycorrhizal infection promoted P nutrition and growth of wheat plants under P deficiency. Therefore VAM efficiency (inoculation effect) was correlated less with % infection (%I, which equals the proportion of infected root in %) than with total infected root length (IRL). Correlations of the inoculation effect on shoot dry weight with %I were 0.28, with IRL 0.47; of the inoculation effect on ear dry weight with %I 0.30, with IRL 0.44; and of the inoculation effect on shoot P uptake with %I 0.53, with IRL 0.58.

The inefficient HYV 'Taifun' (TAI, No.5 in Figure 7) and the high-efficient old variety 'Lohmans Weender Galizischer Kolben' (WG, No.43 in Figure 7) were crossed reciprocally. The old variety WG has 20 cm longer haulms and a larger root system than the semidwarf TAI (Figure 8). Shoot dry weight and haulm and root length of TAI were reduced by VAM inoculation, while the shoot yield of WG was improved by VAM. The high efficiency of WG could be transferred by crossing to the F_1 (Figure 8b). The higher efficiency of WG was correlated with a greater total infected root length compared with TAI, due to greater root length of WG, but with no differences in infection intensity between WG and TAI.

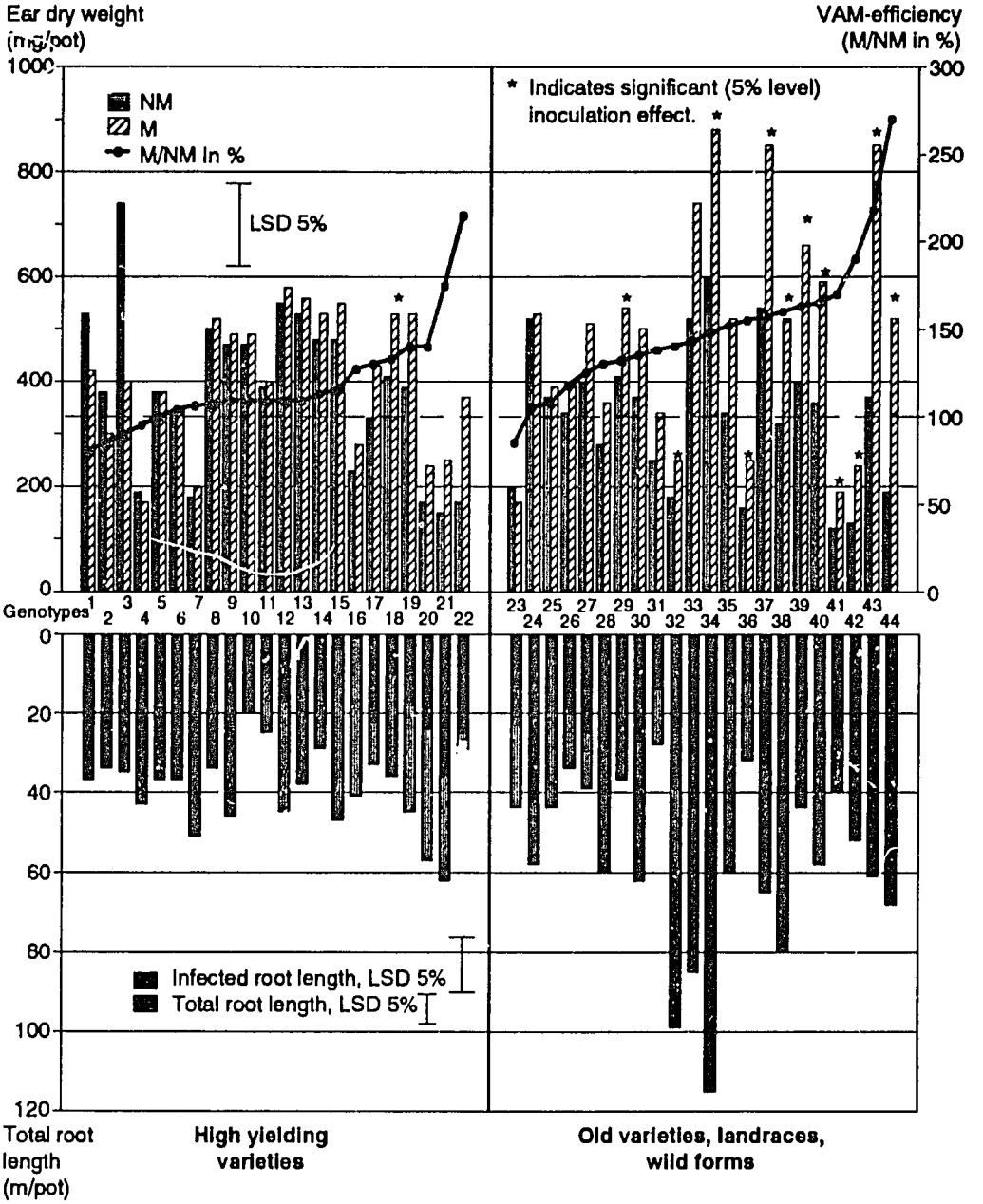
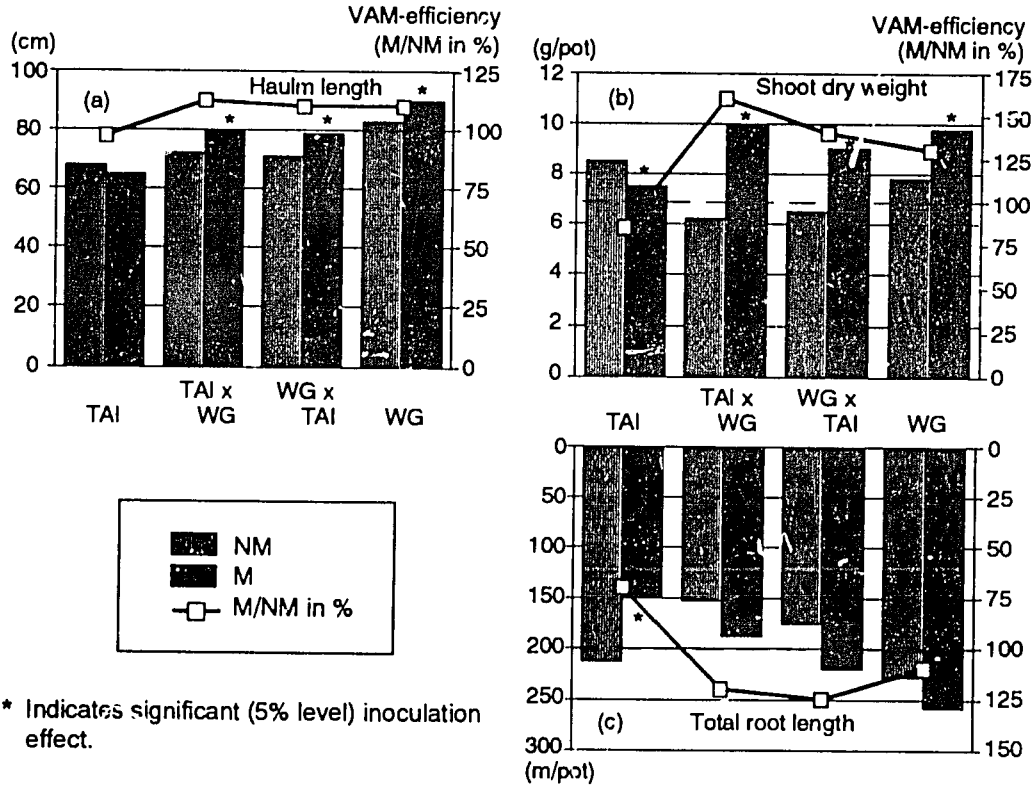


Figure 7. Ear dry weight (mg/pot) and total root length (m/pot) of wheat genotypes (genotypes 1-22, high yielding varieties; genotypes 23-44, old varieties, landraces, or wild forms) when noninoculated (NM) or inoculated (M) with *Glomus manihotis*, in order of ascending VAM efficiency in ear dry weight (M/NM in %). Source: Manske (1989, 1990).

Haulm and root length were positively correlated. The root length of the infected F_1-plants ranged between both parents (Figure 8c). There were no significant differences between the reciprocal crosses, indicating only chromosomal inheritance.

This generation comparison represents the simplest mode of inheritance. During the experiments at IAT, several crossings between different wheat genotypes were conducted (Manske 1989), in which comparison between parental and F_1 generations showed recessive, intermediate or dominant inheritance modes according to crossing combination and environment (P fertilizer form, weather conditions). Dominance was controlled by genes as well as by environmental factors. There were cases of change of dominance within the same genotypes under different environmental conditions. Some of these crossings showed effects of heterosis in VAM colonization and VAM-efficiency (Manske 1990), corresponding with the results of Krishna and Lee (1987) with *Pennisetum americanum*. In some cases, significant differences between reciprocal F_1 generations indicated that plasmatic gene effects also exist in addition to chromosomal ones (Manske 1989).



* Indicates significant (5% level) inoculation effect.

Figure 8. Comparisons of (a) haulm length, (b) shoot dry weight, and (c) total root length between parents (TAI-'Taifun' and WG-'Lohmans Weender Galizischer Kolben') and their reciprocal cross when noninoculated (NM) or inoculated (M) with *Glomus manihotis*. Source: Manske (1989).

Conclusions for Practical Consideration

Although an increasing number of mycorrhizologists has offered a wide spectrum of publications from various research fields, the application of effective VAM fungi to crop production systems under field conditions has been restricted to small-scale field trials because of the lack of inoculum production. The major obstacle faced by researchers at this time is still the inability to produce VAM fungi under axenic conditions. Currently, commercial use of VAM inoculum (produced by the "pot culture" method) is restricted to citrus and avocado nurseries and ornamentals. Under these conditions where seedlings are raised in sterilized soil, the addition of effective mycorrhizal fungi is indispensable to obtain maximum growth. However, limited application of VAM fungi in agricultural production systems should not discourage further research. The examples of this report have clearly demonstrated the potential that VAM can offer, especially for more marginal agricultural lands with soil conditions where available nutrients are of limited supply.

Vesicular-arbuscular mycorrhizal associations should be included in breeding programs of low input-efficient cultivars, especially for marginal soils with P fixation in the tropics and subtropics. Under P deficiency an intense, but also well infected VAM root system can promote P uptake of wheat. Genotypes with intense root systems, but with semidwarf haulm length to avoid lodging, and with high VAM colonization and efficiency can be selected.

If we wish to utilize the mycorrhizal symbiosis effectively in agricultural production programs, mycorrhizal management deserves special attention and a great many agricultural aspects must be taken into account:

- Fertilization level.
- Pesticide application.
- Soil type.
- Plants involved in crop rotation.
- Soil/host combination to which efficient VAM fungi are best suited.
- Interaction with other soilborne microorganisms.
- Competition between exotic and locally adapted VAM strains.

Because VAM fungi occur in all ecosystems, regardless of the crop or cropping system, any disturbance through inappropriate agricultural practices may change the potential of native VAM fungi resulting in a possible decline of productivity and sustainability of the ecosystem. Even the introduction of effective exotic VAM fungi, which had previously been isolated from one soil, may not favor plant growth in another soil or may modify the native population of mycorrhizal fungi due to inter-endophyte competition.

Considering the potential that vescicular-arbuscular mycorrhizal offer, the scale of mycorrhizae research in tropical regions should be substantially expanded with the objective of selecting effective mycorrhizal strains that have favorable associations with a wide array of crops.

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Resumen

Los científicos agrícolas reconocen cada vez más el efecto benéfico de los hongos micorrizales vesiculares-arbusculares (VAM) sobre el desarrollo de los cultivos. La principal ventaja de estos hongos es su capacidad de fomentar la absorción de fósforo por las plantas, en particular en suelos marginales con bajo contenido de nutrimentos y condiciones ambientales extremas. Muchos factores pueden influir en forma decisiva en el desarrollo de los hongos VAM. En este informe se señala y analiza la función crucial de la simbiosis micorrizal en la nutrición de los cultivos con diversas condiciones ambientales y prácticas agronómicas, así como en la fitotecnia. Teniendo en cuenta el potencial de los hongos VAM, se debe ampliar considerablemente la escala de las investigaciones sobre las micorrizas en los países tropicales con el fin de asegurar una aplicación eficaz de esta simbiosis en los sistemas de cultivo de las regiones cálidas.

Nitrogen Fixing Bacteria in Association with Wheat (*Triticum aestivum*)

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Abstract

Biological nitrogen fixation (BNF) by bacteria associated with wheat has been a challenge to soil microbiologists because nitrogen is frequently a principal limiting factor in wheat production in the warmer regions of the developing world where N fertilizers are expensive and less effective. While there is little evidence that wheat can benefit from associated N_2 fixation, over the last 15 years, several new diazotrophic bacteria have been found and investments into research on their association with wheat seem fully justified. Although various Bacillus *and* Pseudonomas *spp. have been found to play a role in association with wheat,* Azospirillum *spp. appear to be the most abundant diazotrophs, principally in warmer regions. A certain specificity of* A. brasilense *for the infection of roots of C3 cereals (including wheat) contrasts with that of* A. lipoferum *for C4 grasses. Certain* A. brasilense *strains isolated from surface sterilized wheat roots could be established in field-grown wheat roots after inoculation causing significant increases of N incorporation and sometimes yield. In ^{15}N dilution experiments, however, it was shown that these strains enhanced nitrate assimilation through more active nitrate reduction in the roots. This was confirmed by the use of the nitrate reductase negative mutants, which had no effect.*

Introduction

Biological nitrogen fixation (BNF) in association with wheat has been a challenge to soil microbiologists for a long time because nitrogen is the major limiting factor for high wheat yields in general and especially in the warmer regions of the developing countries. It is not only that farmers in these countries cannot afford to apply large quantities of nitrogen fertilizer, but also the efficiency of fertilizer use is much lower mainly because of more intense rainfall and rapid organic matter decomposition. In these regions however, the higher temperatures increase the chances of substantial contributions of dinitrogen fixing bacteria for which optimal growth rates are above 25°C (Döbereiner et al. 1975). In Brazil, programs for breeding wheat for high yields with low N fertilizer applications have envisaged the efficient use of soil N and at the same time BNF, and similar programs are in progress in India (Subba Rao 1981). Very few data are available to date which clearly demonstrate the occurrence of any substantial BNF in association with wheat. Perhaps the most convincing data so far are those from the famous Broadbalk experiment at Rothamsted, England, where total N balances in soil and plants after 82 years of continuous wheat revealed gains of 2788 kg N/ha or 34 kg N/ha per year, although this was attributed principally to inputs from algal crusts (cyanobacteria) on the soil surface (Day et al. 1975, Witty et al. 1979).

Diazotrophic Bacteria Found in Association with Wheat

Various diazotrophs have been isolated from rhizosphere soil and from roots and stems of wheat. *Bacillus* sp., probably *Bacillus polymyxa*, has been observed to multiply in the rhizosphere of certain "nonleaky" wheat lines, which were suggested to accumulate rather than

excrete photosynthates and therefore may also support a population of bacteria within the roots (Neal and Larson 1976). A new *Bacillus* species, *B. azotofixans* (Seldin et al. 1984), was isolated from surface-sterilized wheat roots collected in Paraná and Brasilia. This bacterium, in contrast to most other diazotrophs, shows the unusual characteristic of being able to fix N_2 even in the presence of high levels of nitrate, because it does not possess the enzyme nitrate reductase (Seldin et al. 1984). This suggests that BNF associated with this organism should not be affected by nitrate fertilizers. However, in contrast to results with the inoculation of wheat with *B. polymyxa* (Lindberg et al. 1985), the inoculation of wheat grown in monoxenic agar or sand/vermiculite cultures with *B. azotofixans* failed to produce any detectable nitrogenase activity (De Lima and Penido 1989).

Most available data indicate *Azospirillum* spp. as the most abundant diazotrophs associated with wheat, principally in warmer regions. Reynders and Vlassak (1976) found azospirilla present in 40% of soil samples taken from sites all over Belgium and were isolated from 11 wheat root samples out of 14 examined (Vlassak and Reynders 1978), although Harris et al. (1989) found these organisms in less than 1% of 373 cereal root and soil samples in the UK.

In warmer regions, azospirilla are much more abundant in soil and also in association with roots (Table 1). Surface-sterilized wheat roots yielded almost pure *Azospirillum* enrichment cultures, while cultures from nonsterilized roots contained more mixed populations. Kavimandan et al. (1978) were able to isolate azospirilla from wheat stems, confirming the infection and internal translocation of these diazotrophs, as has been shown for rice (Watanabe et al. 1979), maize (Magalhaes et al. 1979), and sorghum (Pereira et al. 1988).

A differentiation between Gramineae possessing the C4 photosynthetic pathway and the C3 cereals was apparent from the observations of Baldani and Döbereiner (1980) and Baldani et al. (1981). With the exception of sugarcane, it was found that the *Azospirillum* population of surface-sterilized roots of C4 plants was composed of more than 80% *A. lipoferum*, whereas roots of wheat, rice, oats, and barley yielded more than 80% *A. brasilense* isolates (Table 2). The *A. brasilense* strains isolated from the surface-sterilized roots of C3 cereals were predominantly nitrite reductase negative (NIR^-).

When certain *Azospirillum* strains were labelled with low-level streptomycin resistance (20 mg/L) and then inoculated into field-grown maize or wheat, more than 80% of the root population seemed to be from the inoculated strains (Baldani and Döbereiner 1980). However, the identification of the inoculated strains

Table 1. Occurrence of *Azospirillum* spp. in wheat roots in Brazil.

Region of Sampling	Latitude	Number of samples	Percent Positive
Juliho Castilho, RGS	30°S	6	17
Cruz Alta, RGS	30°S		
Field I		6	0
Field II		7	100
Londrina, Paraná, various experiments	28°S	100	90
Rio de Janeiro, RJ	23°S		
Plant I thick roots		10	100
fine roots		10	100
Plant II thick roots		10	100
fine roots		10	100

Sources: Döbereiner et al. (1975), Nery et al. (1977).

within surface sterilized roots was complicated by the occurrence, in the control treatment, of high proportions of low level streptomycin-resistant azospirilla (Döbereiner and Baldani 1979). In a separate study, Baldani et al. (1982) found higher numbers of actinomycetes and streptomycin-resistant bacteria in the rhizosphere of wheat than in soil between rows. This enrichment of streptomycin-resistant bacteria in the rhizosphere has also been observed in legumes (Brown 1961).

Significance of BNF Associated with Wheat

Evidence from the acetylene reduction technique

The acetylene reduction technique is a measure of nitrogenase activity (Hardy et al. 1968). When N_2-fixing bacteria are associated with plants, the activity varies considerably with time and is very sensitive to changes in environmental conditions, especially disturbance of the soil (Wani et al. 1983, Minchin et al. 1986). Measurements on intact soil/plant cores with wheat showed large day/night variations in activity from 0.6 μmoles C_2H_4/hr at 4 a.m. to 4.5 μmoles/hr during the day (Döbereiner 1977). Attempts to integrate these data and convert them using the C_2H_4:N_2 ratio of 3:1, to N_2 fixed per core per day, yielded 44 to 597 μg N/ 77.5 cm^2 core at the grain filling stage (Nery et al. 1977). In order to simplify these measures, assays of excised wheat roots pre-incubated overnight at low pO_2 (1-2% O_2) were made, and reasonably good correlations of these results with those obtained from intact soil/plant core assays were obtained (r=0.83** or 0.87**— Nery et al. 1977, Döbereiner 1977) even though the excised root assay showed a slight overestimate in the first study, and

Table 2. Host plant specificity in the infection of surface-sterilized grass roots by *Azospirillum* spp. isolated from field- and pot-grown plants.

Sample	Type of photosynthesis	No. of isolates	% of root[a] isolates identified as *A. lipoferum* NIR+[b]	*A. lipoferum* NIR-	*A. brasilense* NIR+	*A. brasilense* NIR-
Maize	C_4	49	55	41	17	3
Sorghum	C_4	19	20	80	0	0
Forage grasses[c]	C_4	45	33	70	0	7
Sugarcane	C_4	24	0	0	0	100
Cyperus rotundus	C_4	7	0	100	0	0
Wheat	C_3	50	0	0	7	93
Paddy rice[d]	C_3	56	0	0	7	93
Dry rice	C_3	22	7		13	80
Oats	C_3	5	20		0	80
Rye	C_3	22	18		0	82
Barley	C_3	11	18		0	82

[a] Roots sterilized in chloramine T for 0.5 to 60 min. depending on the root structure of each species. Soil samples in almost all harvests contained all three *Azospirillum* groups.

[b] NIR = Dissimilative Nitrite Reductase.

[c] *Panicum maximum, Cynodon dactylon, Pennisetum purpureum, Digitaria decumbens, Hemarthria altissima.*

[d] Includes 34 samples from Trinidad.

Sources: Baldani and Döbereiner (1980), Baldani et al. (1981), Boddey (1980).

almost three times lower values in the second study, in comparison with the intact core technique. For these and other reasons, the excised root assay of nitrogenase activity has been much criticized (Tjepkema and Van Berkum 1977, Van Berkum and Bohlool 1980), and certainly cannot be used for absolute estimates of BNF. But this assay still may have its value for screening large numbers of plant genotypes, or for the detection of the presence of N_2-fixing bacteria. Statistically significant differences between plant genotypes were shown with this method for several cereals (Lee et al. 1977, Von Bulow and Döbereiner 1975, Bouton and Brooks 1982, and Dart and Wani 1982) and also for wheat (Nery et al. 1977).

Evidence from N balance and ^{15}N techniques

Rennie and Larson (1979) studied the N accumulation of several wheat genotypes inoculated with either *Bacillus* spp. strain C-11-25 or *A. brasilense* Sp 7 grown in sterile Leonard jar assemblies in sand/vermiculite and provided with an unspecified amount of nutrient solution containing 100 mg KNO_3/L. This was not a true N balance study as total N in the growth media was not quantified. Five disomic chromosome substitution lines of the wheat genotypes Rescue and Cadet were used and the inoculation promoted large increases in plant dry matter and total N content in several of the lines (especially Rescue C5B and C5D). While this increase in N accumulation could have been due to a BNF input, the lack of information concerning the quantity of KNO_3 added and the total N content of the growth medium leave considerable room for doubt.

In a further study, Rennie et al. (1983) performed a pot experiment on the same genotypes and two Brazilian cultivars grown in soil with the same inocula, but amended with a single application of ^{15}N-labelled potassium nitrate (23 mg N/pot). Inoculation caused either decreases or had no significant effect on total N accumulation by the plants, but for several genotypes, inoculation caused a decrease in the ^{15}N enrichment of the plants. The authors interpreted these results as evidence of contributions of unlabeled nitrogen derived from the air (i.e., BNF) caused by the inoculation of the diazotrophs. However, the ^{15}N-labelled nitrogen was added as a single dose of soluble fertilizer, which would certainly have resulted in a rapid change in ^{15}N enrichment in the soil mineral N with time. And if the inoculation of the diazotrophs caused changes in the growth rates of the plants (and hence soil N uptake patterns), then it is quite possible that the N accumulated by the plants during the season could have achieved different isotope enrichments even if there were no BNF inputs (Witty 1983, Boddey 1987). In a subsequent field experiment carried out in Canada on several other wheat genotypes, very similar results were found (Rennie and Thomas 1987). Again, there were no significant increases in N accumulation caused by the inoculation of *Bacillus* (strain C-11-25) and *A. brasilense* strain Cd, but in some treatments inoculation significantly lowered ^{15}N-enrichment of the plants. Again, the labelled N was added as a single dose of soluble fertilizer and again the different N uptake patterns by the plants could have been responsible for the decreases in ^{15}N-enrichment observed. The authors claimed that as the 'A value' of the soil nitrogen (Fried and Broeshart 1975) determined from the inoculated and uninoculated treatments was nearly always identical, this proved that soil N availability had not changed (with respect to the added labelled fertilizer N) and hence their estimates of BNF inputs were valid. Unfortunately, the authors did not realize that the calculation of the 'A value' was based on the same assumption as the estimates of the BNF inputs and hence cannot be regarded as a test of the suitability of the controls (Boddey et al. 1990).

Two other studies, in pots and in the field, were carried out in Canada and used the same bacteria inoculated onto wheat cultivars (Chester and Fielder) grown in soil amended with a single dose of ^{15}N-labelled fertilizer. These studies also showed significant decreases in plant ^{15}N enrichment, but for the same reasons as described above, these results cannot be regarded as evidence of BNF inputs (Kucey 1988a,b). In the pot experiment, it was found that the inoculation of *Bacillus* or *A. brasilense* significantly influenced the capacity of the wheat roots to absorb nitrate from solution.

Furthermore, the addition of plant growth substances (gibberellic acid or indole acetic acid—IAA) without inoculation of the *Bacillus* or *A. brasilense*, caused significant increases in plant dry matter and N accumulation and decreases in ^{15}N-enrichment of between 12 and 18%. These latter data suggest that the effects of either gibberellic acid, IAA, or the bacterial inocula on plant growth and soil N uptake patterns are sufficient to cause significant differences in ^{15}N-enrichment in the N accumulated by the plant, and that these differences should not necessarily be interpreted as inputs of unlabeled N from BNF.

In a most meticulous ^{15}N dilution study in both soil and monoxenic culture on the effects of inoculation of various *Azospirillum*, *Azotobacter*, and *Bacillus* strains on the Rescue and Cadet cultivars of wheat and the C-R5D and R-C5D substitution lines, Lethbridge and Davidson (1983) failed to detect any consistent responses of plant dry matter or N content to inoculation or any significant BNF inputs.

Two other studies, one in Israel (Kapulnik et al. 1985a) and one in Brazil (Boddey et al. 1986), have been performed on wheat grown in soil amended with ^{15}N and inoculated with various strains of *Azospirillum*. In the Israeli study, the wheat cultivar Miriam was inoculated with a mixture of six *Azospirillum* strains and both at the booting and flowering stages plant dry weight and total N accumulation were increased by inoculation. In the Brazilian study, the wheat cultivar BH1146 was inoculated separately with three *A. brasilense* strains (Sp 245, Sp107, and Sp7) and in all cases the total N content of the grain was increased, on average, by 44%. However, in both studies, the ^{15}N-enrichment of the plant tissue was not changed significantly, indicating that the response to inoculation was not due to a BNF input but to an increased assimilation of soil and fertilizer N.

Specificity in the Association of *Azospirillum* with Wheat Roots

In the case of the legume/*Rhizobium* and other plant/diazotroph symbioses (e.g., *Frankia*/*Alnus*) considerable specificity in the infection of the host plant by the microsymbiont has been observed. Such specificity is also observed in the invasion of roots by pathogenic microorganisms and, as has been pointed out by Holl (1983), it should also be expected in the invasion of grass and cereal roots by *Azospirillum* and other diazotrophs.

Attraction of *Azospirillum* spp. to wheat roots

The first step in the association of a plant pathogen or beneficial microorganism with the plant root is the attraction of that organism to the rhizosphere and root surface. Heinrich and Hess (1985) and Heinrich et al. (1985) reported that *A. lipoferum* strain Sp108 was chemotactically attracted to the root exudates taken from wheat grown in monoxenic conditions. The largest single component of the root exudates was sucrose, which also induced strong chemotactic attraction of Sp108, even though *A. lipoferum* cannot metabolize this sugar. The authors obtained evidence

to show that invertase was excreted by the wheat roots and the resulting fructose + glucose together caused an even stronger chemotactic response by *A. lipoferum*. The strain Sp108 was isolated from maize roots and hence would not be expected to have any particular affinity for wheat roots. Other work on the attraction of *Azospirillum* spp. to wheat roots was carried out using the *A. brasilense* strain Cd (ATCC 29710), isolated from the rhizosphere of *Cynodon dactylon*, and this strain was shown to move up to 30 cm in soil free of roots, when living wheat roots were present beyond this distance; but in the absence of plant roots, movement was negligible (Bashan and Levanony 1987).

Neither of these studies compared the attraction of different *Azospirillum* strains, but Reinhold et al. (1985) showed that *Azospirillum* strain SpT60 isolated from wheat roots was more strongly attracted to oxalic acid (a known major constituent of wheat root exudates—Vancura 1964) than strains isolated from maize, *Cynodon dactylon*, or Kallar grass (*Leptochloa fusca*). Furthermore, SpT60 was less attracted to malic acid (the principal constituent of maize root exudates, but not a major component of wheat root exudates) and the strain ER15 isolated from sterilized roots of Kallar grass was the only one of the four tested strains to be strongly attracted to the exudates of this grass. These data suggest that there may be some specificity in the chemotactic attraction of certain *Azospirillum* strains to wheat roots, but definitive studies have yet to be made.

Adsorption to the root surface

The colonization of the surface of monoxenically grown wheat seedlings (7 to 14 days old) by *A. brasilense* strain Cd was studied using scanning electron microscopy (SEM) by Wallon et al. (1985). The micrographs revealed bacterial growth varying from sparse to heavy on the surfaces of all roots, with growth on the root hairs being sparse near the root tip and sparse to moderately heavy near the seed. Similar images of colonization of pearl millet roots by *A. brasilense* strain Sp7 were obtained using SEM by Umali Garcia et al. (1980), and these authors found that the presence of nitrate (5mM) strongly inhibited the adsorption of this strain to the root hairs, but not to the undifferentiated epidermal cells.

Bashan et al. (1986) studied the adsorption of *A. brasilense* strain Cd to wheat seedling roots 48 h after inoculation. They concluded that there was a weak but active adsorption of the strain Cd to the root surface since light washing of the roots (2 min. with slow stirring) in a phosphate buffer eliminated more than 90% of the bacteria, but cells killed with gamma radiation were not adsorbed significantly. In a similar study on monoxenic wheat plants, the adsorption of five different *Azospirillum* strains on wheat roots was studied (R.M. Boddey and J. Sprent, unpublished data—Table 3). In general, it was found that there were no large differences between strains in the numbers of cells adsorbed to the roots even though the *A. brasilense* strains Sp107, Sp245, and Sp246 were isolated from wheat roots, Cd originated from the rhizosphere soil of *Cynodon dactylon* and S82 from sorghum roots. Washing the roots in phosphate buffer for 30 sec. in a wrist action shaker was sufficient to remove more than 97% of the *Azospirillum* 24 h after inoculation, and more than 90% 120 h after inoculation. There were no apparent differences between strains in the proportion of *Azospirillum* adsorbed to the roots. It should be pointed out, however, that in most legumes no such specificity in the adsorption of *Rhizobium* to the whole root surface has been found, or at least the adsorption is not correlated with the ability of the strain to nodulate the

legume root (Pueppke 1984, Badenoch-Jones et al. 1985, Caetano-Anolles and Favelukes 1986a). It is possible that a reasonably limited number of specific *Azospirillum* adsorption sites on wheat roots are masked by a large number of nonspecific sites as was suggested to be the case for the adsorption of *Rhizobium* to alfalfa roots (Caetano-Anolles and Favelukes 1986b).

Effects of *Azospirillum* on root hair deformations

Strain specificity has been demonstrated in the effects of *Azospirillum* on root hair deformations in wheat seedlings. Patriquin et al. (1983) observed that branched root hairs were more common in seedlings inoculated with *A. brasilense* Sp 245 than in uninoculated seedlings or those inoculated with strains Sp7 and Sp 107. Branching was classified into two types, branches of equal length, the "tuning-fork deformations" and branching of unequal length. Seedlings grown in semisolid agar in test tubes or germinated on water agar plates exhibited the tuning-fork deformation only in the presence of *Azospirillum*, with one exception among 125 such deformations observed. Unequally branched root hairs were observed in most uninoculated controls. The order of frequencies of the tuning-fork deformations in seedlings inoculated with different strains was consistently *A. brasilense* strain 245 > strain Sp107 > strain Sp7 ≥ *Azospirillum* sp. strain Sp242. This order corresponds to the order of total N gains in wheat following inoculation of field grown plants with the same strains (Baldani et al. 1983). Only strains Sp245 and Sp107 were isolated from (surface-sterilized) wheat roots. Few or no tuning-fork deformations were

Table 3. Number of viable cells of *Azospirillum* spp. adsorbed to, and removed by washing in phosphate buffer from, wheat roots (cv. IAC 5) inoculated with five strains of *Azospirillum*.

Strain	No. of viable cells of *Azospirillum* (x 10^6) Washed from roots after 30 sec.	30 min.	Macerated roots	% adsorption[a]
Exposure 24 hours				
Cd	3.38 ± 0.34	3.70 ± 0.88	0.066 ± 0.023	1.83 ± 0.47
Sp245	2.88 ± 1.28	3.51 ± 1.94	0.090 ± 0.036	2.03 ± 0.59
Sp246	3.12 ± 0.37	3.10 ± 1.00	0.076 ± 0.048	2.71 ± 1.92
Sp107	1.22 ± 0.16	1.64 ± 0.67	0.027 ± 0.013	1.66 ± 0.45
S82	19.57 ± 10.38	20.80 ± 10.93	0.544 ± 0.310	2.58 ± 0.19
Exposure 120 hours				
Cd	13.6 ± 3.2	19.3 ± 5.6	1.90 ± 1.21	9.57 ± 3.88
Sp245	47.3 ± 3.6	70.2 ± 18.4	2.81 ± 0.53	8.00 ± 3.10
Sp246	86.4 ± 39.7	98.6 ± 33.8	4.68 ± 0.55	6.23 ± 1.48
Sp107	78.9 ± 40.9	107.0 ± 69.7	4.59 ± 2.66	6.20 ± 1.99
S82	61.9 ± 28.7	74.9 ± 47.0	2.09 ± 0.28	4.17 ± 1.40

[a] Number of *Azospirillum* cells in/on roots after washing for 30 minutes x 100/number of *Azospirillum* cells in suspension.

± standard error of the mean.

produced by strains not isolated from wheat roots (Sp7 and Sp242). Addition of N in most cases increased the number of deformations in contrast to the reported inhibition of legume root hair deformation by ammonium or nitrate (Dart 1974).

Infection of the root interior

That azospirilla can enter cereal and grass roots and invade the cortex is now firmly established (Patriquin and Döbereiner 1978, Schank et al. 1979). By using the immuno-gold technique, Bashan and Levanony (1988) showed the presence of *A. brasilense* strain Cd within the intercellular spaces of the root cortex of wheat.

Evidence for the occurrence of strain specificity in the infection of wheat roots by *Azospirillum* comes not only from the observation (reported above) that most strains isolated from surface sterilized roots are *A. brasilense* NIR⁻, but also from inoculation experiments. Baldani et al. (1986) showed that two strains isolated from surface-sterilized wheat roots (Sp107st and Sp245spec) could be re-isolated from 82 and 76% of the highest dilution vials of most probable number (MPN) counts of surface-sterilized wheat roots inoculated with these strains, while in similar counts on roots inoculated with strain Sp7 (*A. brasilense* NIR⁺ isolated from soil) this strain only occurred in 11% of the vials. Similar observations were made in the field with eight wheat cultivars in an experiment performed in Paraná (Baldani et al. 1986). In contrast to the data obtained in Brazil, where Azospirillum numbers in soils are always high, data from Israel indicate that strain Cd could be established in a large number of field experiments in numbers around 10^5 to 10^6 g/washed root (Bashan et al. 1987) and maintained at these levels during the growth cycle of wheat. Apparently, in Israeli soils, the natural occurrence of *Azospirillum* spp. is negligible.

Response of Wheat to Inoculation with *Azospirillum* spp.

Apart from the studies cited above, there are many other reports of responses of wheat to inoculation with *Azospirillum* spp. Positive responses of grain yield, dry matter, and the accumulation of nitrogen and other nutrients caused by the inoculation of wheat with *A. brasilense* strains Cd and Sp7 have been reported from many field experiments carried out in Israel (Kapulnik et al. 1981, 1983, 1987; Millet et al. 1985). Even in the cooler climates of Belgium and Germany, positive results have been reported with other *Azospirillum* strains (Reynders and Vlassak 1982, Mertens and Hess 1984). While some positive results have been obtained on soils of very low fertility (Mertens and Hess 1984), more reports of inoculation responses have been obtained at medium or high levels of N fertility (Avivi and Feldman 1982, Reynders and Vlassak 1982, Kapulnik et al. 1983, Zambre et al. 1984). These results are consistent with those obtained using the ^{15}N isotope dilution technique (previously cited) in that they suggest the responses were not due to BNF contributions.

It should not be imagined that there are consistent positive responses of wheat to *Azospirillum* inoculation. Apart from the fact that zero or negative responses are rarely reported, even in the published literature several studies reveal such data (Lethbridge and Davidson 1983, Kapulnik et al. 1987, O'Hara et al. 1987, Haahtela et al. 1988). In addition, there is some evidence of a plant genotype effect (Millet et al. 1984, Kucey 1988b). In a study on the inoculation of eight Israeli wheat cultivars with a mixture of *A. brasilense* strains, Kapulnik et al. (1987) found that the grain yield of only one cultivar, Miriam, responded significantly to inoculation (25% increase in yield) and that three other cultivars showed significant reductions in grain yield.

A further reason for the lack of response seems to be in the failure of the inoculated strain to establish in or on the roots of wheat. Apart from the aforementioned study of Bashan et al. (1987), almost the only studies where the establishment of the inoculated strain was evaluated during crop growth are those performed by our group in Brazil. For example, Baldani et al. (1983) found that when field-grown wheat was inoculated separately with several strains of *Azospirillum* isolated from wheat and maize roots, the two strains which consistently established within wheat roots (i.e., dominated the *Azospirillum* population of surface-sterilized roots), and caused the largest responses to inoculation, were precisely those originally isolated from surface-sterilized wheat roots (Sp245 and Sp107). The strains isolated from maize (Sp242 and Sp108) and a strain isolated from the rhizosphere soil of wheat (SpBr14) showed considerably lower numbers within the root and induced much smaller responses to inoculation. There was a close correlation (r = 0.924**) over all six treatments, between numbers of *Azospirillum* isolated from surface sterilized roots and the total N accumulation by the plants. No significant correlation (r = 0.52) was observed between total *Azospirillum* numbers isolated from nonsterilized (washed) roots and N accumulation (Baldani et al. 1983). These results constitute strong evidence it is those azospirilla that invade the root tissue which promoted the observed responses to inoculation.

Similar results, showing that *Azospirillum* strains isolated from the interior of wheat roots are those that establish in wheat roots and cause the greatest responses of wheat plants to inoculation, have been recorded in other studies by our group (Baldani et al. 1986, 1987). Recent experiments using oil-based and peat-based inocula showed that the former failed to establish significant numbers of *A. brasilense* Sp245 within wheat roots or induce any significant inoculation response, whereas the peat-based inoculum was successful in both respects (Table 4). In several recent

Table 4. Effect of oil- or peat-based inoculants of *Azospirillum brasilense* (Sp245) on the establishment of strain Sp245 in/on wheat roots, and the yield and N incorporation in field-grown wheat (cv. Anahuac) at the flowering stage. Means of six replicates.

	% of vials containing[a] inoculated strain					
	Washed roots	Surf. Ster[b] roots	Dry weight (g/plot)[c]	% N	Total N (mg/plot)[c]	Grain yield (kg/ha)
Sp245[d] (Peat)	72	89	186a	0.89	1.66a	1057a
Sp245[d] (Oil)	39	0	155ab	0.79	1.23ab	950ab
Control (-N)	17	0	116b	0.76	0.88b	781b
Control (+N) 60 kg N/ha	not determined		151ab	0.87	1.32ab	1008ab

[a] Percentage calculated from 18 vials (three from each replicate from the highest *Azospirillum*-positive MPN dilution vials).
[b] 15 min. in chloramine T.
[c] Plot size = 2.5 m².
[d] Spontaneous mutant resistant to 20 ppm streptomycin and 80 ppm spectinomycin.

Sources: V.L.D. Baldani, J.I. Baldani, J. Mandel, and J. Döbereiner (unpublished).

studies on the inoculation of wheat with various *A. brasilense* strains, we have failed to observe any responses to inoculation, but this has always coincided with low population of the inoculated strain within the root, again emphasizing the importance of good establishment of the strain if effects on plant growth are to be observed (Boddey and Döbereiner, unpublished data).

Mechanism of the Response of Wheat to *Azospirillum* Inoculation

The general consensus deduced from ^{15}N and other studies is that the observed responses of wheat to inoculation with *Azospirillum* is mainly due to causes other than BNF inputs (Okon 1985, Okon and Hadar 1987, Bashan and Levanony 1988, Boddey and Döbereiner 1988). Several mechanisms have been invoked to explain these responses, especially the production of plant growth substances, such as indole acetic and gibberellic acids, either produced by the bacteria or produced by the plant in response to inoculation. It is firmly established that azospirilla can produce IAA in culture media, although the evidence for the production of gibberellic acid is more controversial (Reynders and Vlassk 1979, Tien et al. 1979, Hartmann et al. 1983, Jain and Patriquin 1985, Zimmer and Bothe 1988). The evidence obtained by Jain and Patriquin (1984, 1985) indicate that IAA production by *Azospirillum* was responsible for the strain specific root hair deformations that they observed. Several authors have reported changes in root length, and length and number of roots hairs, of young wheat plants caused by the inoculation of *Azospirillum* in monoxenic and nonsterile culture (Inbal and Feldman 1982, Patriquin et al. 1983, Kapulnik et al. 1985b, Del Gallo 1986) and there seems little doubt that IAA and/or other growth substances are responsible. Both Kapulnik et al. (1985b) and Bashan (1986) reported that the root surface area of wheat seedlings was increased by inoculation with *A. brasilense*, and Bashan et al. (1989) reported that proton efflux of wheat roots was increased.

Zimmer and Bothe (1988) found that the response of young wheat roots grown in monoxenic conditions to inoculation with *A. brasilense* was much greater if the hydroponic solution contained nitrate rather than ammonium. Under these conditions they isolated a compound which had phytohormonal properties and which was subsequently found to be nitrite (Zimmer et al. 1988).

Data from our laboratory also suggest a role of nitrite in the response of wheat to inoculation of *Azospirillum* (Ferreira et al. 1987). The inoculation of monoxenic wheat plants with *A. brasilense* strain Sp245 and nitrate reductase negative (NR^-) mutants of Sp245, showed that the wild type strain promoted significant increases in shoot and root fresh weight and significant acetylene reduction activity (ARA) in the presence of 1mM nitrate, but ARA was lower and there was no response to inoculation with the NR^- mutants (Table 5). In the presence of 10 mM nitrate the ARA of the plants inoculated with the wild type was totally inhibited, but this activity was not affected in the plants inoculated with the mutants. Higher leaf nitrate reductase activity was observed in the leaves of plants inoculated with the NR^- mutants which indicated that the nitrate was translocated to the tops in an unreduced form, while the parent strain aided nitrate reduction in the roots causing a decrease in NR activity in the leaves (Table 5). These data suggest a role of bacterial nitrate reductase in the enhanced N assimilation by wheat plants inoculated with *A. brasilense* strain

Sp245, which was confirmed by the ^{15}N-labelled fertilizer assimilation observed in the field experiment discussed above (Boddey et al. 1986). A further experiment performed in the field confirmed that the NR^- mutant was far less effective than the NR^+ parent strain at promoting inoculation responses of dry matter and N content of wheat (Baldani et al. 1986). Furthermore, the data indicated that, while the parent strain Sp245 dominated the *Azospirillum* population of the root interior, the NR^- mutant failed to establish at this site.

Other studies have indicated that *Azospirillum* inoculation increases the uptake of nitrate (Kapulnik et al. 1985c, Kucey 1988b) and other nutrients by wheat plants (Kapulnik et al. 1987). However, these effects may be secondary, caused by general increases in plant growth due to increased root length or other mechanisms. Recently, Bashan et al. (1990) found that different strains inoculated onto different wheat cultivars produced inconsistent changes in uptake of mineral elements, and they concluded that although *A. brasilense* strains are capable of changing the mineral balance and content of plants, it is unlikely that this ability is a general mechanism responsible for improved plant growth.

Concluding Remarks

Very recent unpublished data from our research team indicate that not all hope is lost for the occurrence of BNF in association with wheat. Almost all efforts in this direction have concentrated either on the *A. brasilense* strains Sp7 or Cd isolated from soil (see most of the Israeli work reported here) or on strains isolated from surface-sterilized wheat roots such as Sp245 and Sp107, which consistently establish within roots. A number of *A. brasilense* strains isolated from washed roots of wheat grown without N fertilizer in the major Brazilian wheat growing area of Rio Grande do Sul, however, showed a surprising correlation of *in vitro* acetylene reduction activity with plant responses to inoculation (Table 6). In these experiments strain Sp245 showed the smallest plant response and also the lowest nitrogenase activity. One could therefore imagine inoculants containing *azospirilla* strains that infect roots and promote wheat growth by more efficient

Table 5. Effects of inoculation of *A. brasilense* and its nitrate reductase negative mutant on wheat plants grown monoxenically in tubes for 15 days.

Inoculation treatment	NO_3 conc. (mM)	Plant fresh wt. (g/tube)	ARA (n moles C_2H_4-/tube/h)	Nitrate reductase activity in leaves (µmol NO_2/g/h)
Control	1	0.38c	0.00d	0.49f
Sp7	1	0.35c	2.56b	0.42f
Sp245	1	0.47d	4.03a	1.01e
Sp245 NR^-	1	0.37d	1.56c	1.24d
Control	10	0.51c	0.00d	2.01b
Sp7	10	0.46d	0.00d	2.31b
Sp245	10	0.70a	0.00d	1.65c
Sp245 NR^-	10	0.56b	1.42c	5.47a

Means followed by the same letter are not significantly different at P=0.05 (Tukey test).

Source: Ferreira et al. (1987).

use of N fertilizer caused by bacterial nitrate reductase, together with other strains which proliferate on the roots surface (now depleted of nitrate by the enhanced nitrate assimilation) fixing N_2 which eventually might be available for the plant. So far, however, this is all only a dream!

Table 6. Comparison of acetylene reduction activity in 10-day-old seedlings, and plant growth (30 days) in sand irrigated with N-free nutrient solution.

Azospirillum isolate	Source	ARA (n moles C_2H_4/h)	Root wt. (g/pot)	Plant wt. (g/pot)	% Increase over control
JA4[a]	Washed	292	3.13	4.54	104
JA18[a]	Washed	145	2.55	4.13	85
JA13[a]	Washed	136	2.05	3.42	53
JA2[a]	Washed	136	4.48	6.02	169
JA3[a]	Washed	54	1.86	3.52	58
JA11	Surface sterile	64	2.01	3.37	51
Sp245	Surface sterile	17	1.30	2.58	16
Control		1	0.40	2.23	0
Control + 60 ppm N		-	1.60	4.36	140

[a] Isolates from washed roots of wheat lines selected for high yields in poor soil without N fertilizer in Rio Grande do Sul (temperate climate, south of Brazil).

Source: A.D. Didonet and J.O. Mendel (unpublished data).

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Resumen

La fijación biológica del nitrógeno por bacterias asociadas con el trigo ha representado un desafío para los microbiólogos del suelo porque ese elemento suele constituir un importante factor limitante de la producción de trigo en las zonas cálidas del mundo en desarrollo donde los fertilizantes nitrogenados son costosos y menos eficaces. Aunque hay pocos datos que indiquen que el trigo puede beneficiarse con la fijación asociada de N_2, en los últimos 15 años se han encontrado varias bacterias diazotróficas nuevas y parece plenamente justificada la inversión en investigaciones sobre la relación de esas bacterias con el trigo. Si bien se ha comprobado que diversas especies Bacillus *y* Pseudomonas *desempeñan una función relacionada con el trigo, las especies* Azospirillum *parecen ser los diazotrofos más abundantes, principalmente en las regiones cálidas. Cierta especificidad de* A. brasilense *para la infección de las raíces de los cereales C3 (incluido el trigo) contrasta con la de* A. lipoferum *para las gramíneas C4. Algunas cepas de* A. brasilense *aisladas de raíces de trigo cuya superficie ha sido esterilizada, pudieron establecerse después de ser inoculadas en raíces de trigo cultivado en el campo, y causaron aumentos considerables de la incorporación de N y, algunas veces, del rendimiento. Sin embargo, en experimentos con diluciones de N^{15} se comprobó que estas cepas intensificaban la asimilación de nitratos mediante la reducción más activa de los nitratos en las raíces. Este hecho fue confirmado usando los mutantes negativos respecto a la nitrato reductasa, que no produjeron ningún efecto.*

Triticale in the Warmer Areas: Is Its Efficiency in Nutrient Uptake Enough to Bring Farmer Acceptance?

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Abstract

Cultivation of triticale (X Triticosecale *Wittmack;* Triticum turgidosecale *[Kiss] MK) has expanded rapidly in many regions of the world because of its improved disease resistance, yield potential, and improved grain quality. It is cultivated extensively on acidic and sandy soils of the temperate climates (i.e., Russia, Poland, France) in traditional rye areas. It is also cultivated and will further develop in the humid and semiarid subtropical environments. In the humid subtropics with acid soils, triticale's potential relies on its broad disease resistance; high yield potential; tolerance to toxicities of aluminum, manganese, and/or iron; and its efficiency in phosphorus uptake. In semiarid regions with drought or salinity stresses, adaptation is related to tolerance to boron toxicity and efficiency in utilizing water, copper, manganese, and zinc.*

Combining yield potential and grain quality with the characteristic hardiness of rye increases the potential of triticale for many warmer nontraditional, small grain growing areas. In southern Brazil, triticale has shown its best adaptation on the acid soils located at altitudes higher than 500 meters above sea level. At lower altitudes or in dryland cultivation in central Brazil, where mean temperatures during tillering exceed 14°C, triticale does not perform well and most institutions have discontinued their investigation.

Introduction

The progress of triticale research during the last 20 years has been tremendous. A species with tall and late plants, susceptibility to most wheat diseases, and poor grains was transformed into a crop with enormous potential for environments that have not been traditional for wheat cultivation (Varughese et al. 1986), especially for the poor and acidic soils, the tropical highlands, and the semiarid regions where complete triticales perform best (Varughese et al. 1987). Currently, triticale is cultivated primarily in temperate climates, like those in Poland, Russia, France, and Canada.

The future of the crop now seems free of fundamental agronomic obstacles. A mere 3 decades after the first practical triticales were developed, the crop is posed for commercial production. It has particular promise as a supplement to current foods, feeds, and brewing grains. Its greatest promise is probably in locations where wheat is an unreliable crop. Triticale shows high yields in acid soils (with high soluble aluminum) and on phosphorus-fixing soils. On acid soils, the crop's potential is unmatched by wheat, demonstrated in Poland, Kenya, Ethiopia, India, Ecuador, Brazil, Mexico, and elsewhere. Many of these countries import large amounts of wheat and could benefit greatly from a locally grown bread grain (National Research Council 1989).

Breeding for nutritional characters is not common in cereal improvement programs. This may be seen as a tribute to

agronomists who have successfully modified the soil environment with fertilizers to suit the plant that breeders have produced—thus allowing the latter to concentrate on the more pressing problems of yield, climatic adaptation, quality, and resistance to pests and diseases. To argue that we should breed for nutritional characters, it is necessary to show a need as urgent as some of the other objectives, that there exists meaningful genetic potential, and that it is agronomically, economically, and ecologically feasible (Graham 1984).

In the recent past, there has been a large increase in human consumption of wheat products, reflected, for example, by the increase in global wheat importation by developing countries from 30 to 62 million tons during the 1970-83 period (CIMMYT 1983). Between 1985 and 2000, an annual 3% increase in wheat consumption is foreseen in the developing world (CIMMYT 1989). This great requirement for wheat by developing countries could be supplied, in part, with triticale.

Adaptation to Semi-arid Regions

Lopez and Garbini (1985) reported that triticale has potential for cultivation—as a substitute for rye—in the huge semi-arid regions of the Southern Cone (i.e., western Buenos Aires Province and eastern La Pampa Province), where the climate is highly unstable and annual rainfall is between 400 and 700 mm.

Francois et al. (1988) considered the triticale varieties, Beaguelita and Cananea, tolerant to salinity because yield reductions occurred only at higher salt concentrations. Superior tolerance to salinity has been observed in varieties of triticale at the initial growth stages when compared to wheat and barley, but this did not translate to higher yields, possibly because of water and heat stresses at maturity.

Some triticale varieties (e.g., Flora in the USA) have been released for cultivation on alkaline soils (National Research Council 1989).

In experiments with sandy, copper-deficient soils of Southern Australia, Graham (1978) demonstrated that rye and triticale extract this element more efficiently than does wheat. This character is controlled by genes carried on the long arm of rye chromosome 5R and can be transferred to wheat (Graham et al. 1987).

In copper-deficient soils—although the element is present—it is unavailable for common varieties of wheat, which makes them more susceptible to diseases; this is not a problem with rye and triticale (Graham et al. 1987). Kaur and Takkar (1987) evaluated eight wheat lines and one triticale line on a highly alkaline soil (pH 8.8) with manganese deficiency. They concluded that the triticale TL419 and wheat variety C306 could be considered tolerant and recommended them for commercial cultivation in manganese-deficient soils. The remaining wheats had varying degrees of susceptibility.

Graham (1984) concluded that, among the small grain cereals, rye has the greatest ability to absorb copper, zinc, manganese, and phosphorus. The difference in this character between wheat and rye demonstrates the immense genetic variability available. Triticale, in general, has a reaction intermediate between wheat and rye.

Toxicity tolerance to the heavy metals (copper, zinc, nickel, cadmium, mercury, and lead) received much attention in recent decades, but very little research has been directed towards cereals (Graham 1984). Breeders should also direct attention toward selection procedures for water use efficiency because, in comparison to wheat, rye

needs only 70 to 80% of the water to produce the same amount of dry matter (Bushuk 1976).

Adaptation to Acid Soils

Triticale is cultivated extensively for grazing and grain production in New South Wales, Australia, because of its resistance to diseases and adaptation to acid soils in environments with heavier rainfall (Gammie 1986). The potential of triticale as an economic crop for the highlands of Rwanda and Burundi is demonstrated by Van Der Pahlen (1986) where disease resistance, vigor, and adaptation to acid and sandy soils are important characters. In Madagascar, where phosphorus-fixing acid soils prevail, triticale has shown high potential in nonirrigated fields (Rakotondramanana 1986).

Aniol (1985) compared more than 300 varieties and lines of triticale selected in Poland and found that 50% were more resistant to aluminum than the wheat variety BH1146, considered one of the most resistant wheats under Brazilian subtropical conditions. It was also observed that most varieties and lines segregated for this character, meaning that the resistance of triticale to acid soils can be improved if selected carefully.

Camargo and Felicio (1987) concluded that Centeio Branco (white rye) and the triticale line TCEP 77138 (CEP 15) had better tolerance to aluminum toxicity than the most tolerant wheats in solutions containing up to 10 mg Al^{+++}/L. Jessop et al. (1986) evaluated the tolerance to soil acidity and aluminum toxicity under field conditions and in solutions and concluded that triticale was tolerant under both conditions, but that there were differences between field observations and the results obtained in solutions, which may have been conditioned by manganese toxicity and phosphorus deficiency.

Rosa and Ben (1986) studied the efficiency of phosphorus utilization on soil with a pH of 4.6, low available phosphorus (1 ppm/dL soil), and high concentrations of aluminum (2.4 me/dL soil). They observed that the performance of triticale varieties was comparable to the most efficient wheat varieties and that the rye populations from the very acid soils with extremely low phosphorus availability of southern Brazil had excellent development. They concluded that rye's good efficiency to utilize phosphorus may be due to natural selection.

Ben (1989) evaluated a triticale and a group of wheat lines selected for phosphorus utilization efficiency. He applied 0 and 80 kg P_2O_5/ha to a soil with pH of 4.8, 2.9 me/dL of Al^{+++} and 4.5 ppm of available phosphorus. The triticale BR1 was in the group of genotypes that had high yield in the absence of fertilizer and had the best response to fertilizer application.

Brooke et al. (1989) compared varieties of different species at two levels of lime application on soils having free aluminum and manganese. Lupins had the lowest response to lime application; oats and triticales had low yield responses to lime—equal to the most tolerant wheat varieties; most wheat varieties had a large response. The use of tolerant varieties may offer an alternative to liming, which can induce increased disease problems, e.g., take-all (Murray et al. 1987).

Camargo et al. (1988) state that triticale and rye are well known for tolerance to high levels of toxic aluminum and iron. Comparing the responses of wheat, triticale, and rye to Fe^{+++} concentrations between 0.56 and 40.0 mg/L, they observed that there was a reduction in root length in all three species, but that the wheat variety IAC-74 and the triticale varieties PFT 7719, PFT 7882 (Tarasca), and TCEP 7889 (CEP 18) had combined

tolerance to iron and aluminum toxicities and should be considered as valuable sources to breeding for tolerance. Iron toxicity is recognized by the yellowing of the lower leaves and is a serious problem of many crops growing on acid soils.

Triticale's Resistance to Aphids and Viruses

Aphids and the barley yellow dwarf virus (BYDV) that they transmit frequently reduce yields in the nontraditional areas. Comeau and St-Pierre (1988) stated that triticale should be considered as an excellent source of resistance to both the aphids and the disease and demonstrated that when there are aphid infestations in dry years, the aphid resistance improves tolerance to drought stress.

Resistance evaluations made under controlled conditions at the National Research Center for Wheat demonstrated that triticale is resistant to *Schizaphis graminum* (Ottoni Rosa, pers. comm.). In field observations the resistance of triticale to aphids has been confirmed—especially under heavy infestations.

In some regions of southern Brazil, it was observed that after soil amendment with lime, there is an increase in soilborne wheat mosaic virus (SWMV) to which most triticale lines also are resistant.

Triticale's Adaptation to Acid Soils in Southern Brazil

Triticale varieties from all over the world have been evaluated in Brazil since 1969. Only material from CIMMYT has had acceptable adaptation. The first agronomically acceptable genotypes were identified in 1976 when some lines with substituted chromosomes produced better grain. Triticale BR 1 and CEP 15—Panda lines—became the first cultivated triticale varieties in Brazil due to their resistance to rust and mildew, adaptation to acid soils, and yield potential.

Later, a group of complete triticale lines, represented by OCEPAR 1 and CEP 22, were identified to have high plant vigor, better resistance to spike diseases, and higher yield potential (Tables 1 and 2).

Felicio et al. (1987) concluded that a group of varieties evaluated at three locations in the state of São Paulo between 1982 and 1984 had higher yield, resistance to rusts, and spike infertility "chochamento" than the wheat varieties, although these had a higher test weight.

Baier and Nedel (1986) and Baier (1989b) emphasized the potential and advantages of triticale as well as the limitations for its cultivation on the extensive under-utilized areas of southern Brazil during winter, with acid soils, low phosphorus availability, and aluminum toxicity.

Through the evaluation of five triticale lines in Passo Fundo, Baier (1989a) concluded that the complete line PFT 8512 (Triticale BR 4) performed better over all environments tested. He used direct tilling over 2 years on soil with pHs from 4.2 to 5.0 and Al^{+++} between 1.8 and 4.1 me/dL of soil, with and without partial amendment and fertilization. W.H. Pfeiffer (pers. comm.), in an analysis of this study, concluded that while significant differences occurred between genotypes and environments, there were no G x E interactions (possibly due to the limited number of genotypes used). The largest separation of genotypes occurred when soil with partial lime amendment and intermediate pH levels and Al^{+++} concentrations was used.

The Brazilian Triticale Yield Trial (Ensaio Brasileiro de Triticale), sown annually at more than 20 locations in the main wheat growing regions since 1977, indicates that the greatest potential for triticale in southern Brazil is on the acid soils located at altitudes above 500 meters above sea level (masl), represented by Passo Fundo

(Tables 1-4). Passo Fundo's altitude is 684 masl and average temperature of the coolest month (July) is 12.5°C. Similar results were obtained in Cruz Alta and Lagoa Vermelha in Rio Grande do Sul, all locations in Santa Catarina and Ponta Grossa, and Guarapuava and Irati in the State of Paraná. Acid soils, higher organic matter content of the soil, elevations higher than 500 masl, and similar temperatures during the coolest month of the year are common to these areas.

Table 1. Yields (t/ha) of triticale and wheat varieties at three locations in southern Brazil, 1987-1989.

	Passo Fundo			São Borja[a]			Cascavel[a]		
Altitude (masl):	684			99			760		
Mean Temp. (°C):	12.5			14.5			13.8		
Latitude:	28°04'			28°45'			24°56'		
Year:	87	88	89	87	88	89	87	88	89
Triticale BR 1	3.9	3.9	4.5	2.6	2.6	1.9	2.8	3.2	1.4
OCEPAR 1	5.3	5.3	6.3	3.4	3.1	1.2	3.2	3.6	1.1
CEP 22	6.5	5.7	6.9	4.3	3.4	1.6	3.3	3.6	1.5
IAPAR 23	5.6	5.2	5.9	3.8	3.2	1.9	3.7	4.0	1.7
PFT 8710	-	-	7.2	-	-	2.3	-	-	1.3
Wheat[b]	4.6	3.1	4.4	3.6	2.9	2.1	1.9	3.2	0.8

[a] São Borja data were provided by Ari Caumo and Danilo Bohn, Instituto Pesquisas Agronômicas (IPAGRO) of Rio Grande do Sul; data from Cascavel were provided by Manoel Bassoi and Francisco Franco of OCEPAR-Pesquisa.

[b] Wheat varieties were: CEP 11 in Passo Fundo, CNT 8 in São Borja, and CEP 7780 in Cascavel in 1987; CEP 11 in Passo Fundo and Cascavel, BR 14 in São Borja in 1988; and CEP 21 in Passo Fundo, BR 32 in São Paulo, and IAC 5 in Cascavel in 1988. All wheat varieties are well adapted to the acid soils and are aluminum tolerant.

Table 2. Average of eight scab and helminthosporium observations on triticale and wheat varieties in Passo Fundo in 1989.

Variety	Helminthosporium[a]	Scab[a]
Triticale BR 1	8	7
OCEPAR 1	5	4.9
CEP 22	2.2	5.2
IAPAR 23	2.3	4
PFT 8710	3.2	4.4
Wheat (BR 14-Thombird)	3.2	5.6

[a] Scale used: 1 = very resistant, 9 = very susceptible.

Another achievement came with a group of lines that, in addition to having the previously mentioned advantages, have improved test weights, represented in Table 3 by IAPAR 23 and PFT 8710—TAPIR/YOGUI//*MUS, CTM15062-019M-23Y-0M-0Y. PFT 8710 also has lower amylase activity with higher Hagberg's Falling Numbers (Table 4). Triticale lines have lower sedimentation values than wheat.

At lower altitudes in southern Brazil and summer dryland areas in central Brazil (lower latitudes), most institutions have

stopped evaluating triticale because the available germplasm did not offer advantages over wheat. Average temperatures during tillering in central Brazil range between 17 and 18°C and between 16 and 17°C in Dourados and Ponta Pora, Mato Grosso do Sul. The results from São Borja (Table 1) and the dryland trial from Ponta Pora (Table 5) demonstrate that the relative advantage of triticale is not large and serve as examples for the remaining regions in southern Brazil where evaluation of triticale was discontinued. Baier et al. (1983) concluded that high temperatures and water stress during tillering and helminthosporium and scab at the end of the cycle are probably the main limiting

Table 3. Test weights (kg/hl) of triticale and wheat varieties at three locations in southern Brazil in 1987-1989.

	Passo Fundo			São Borja[a]			Cascavel[a]		
Variety	87	88	89	87	88	89	87	88	89
Triticale BR 1	66	71	70	69	70	69	76	76	<65
OCEPAR 1	71	75	73	72	69	67	69	71	<65
CEP 22	72	76	72	72	70	78	69	71	<65
IAPAR 23	73	78	74	75	75	72	75	78	69
PFT 8710	-	-	77	-	-	73	-	-	68
Wheat[b]	77	77	79	79	77	79	80	83	67

[a] Data from São Borja were provided by Ari Caumo and Danilo Bohn from Instituto Pesquisas Agronômicas (IPAGRO) of Rio Grande do Sul. Data from Cascavel were provided by Manoel Bassoi and Francisco Franco of OCEPAR-Pesquisa.

[b] Wheat varieties were: CEP 11 in Passo Fundo, CNT 8 in São Borja, and CEP 7780 in Cascavel in 1987; CEP in Passo Fundo and Cascavel and BR 14 in São Borja in 1988; and CEP 21 in Passo Fundo, BR 32 in São Borja, and IAC 5 in Cascavel in 1989. Wheat varieties are well adapted to acid soils and are aluminum tolerant.

Table 4. Hagberg's falling numbers and sedimentation with SDS obtained from triticale and wheat at three locations in southern Brazil in 1989.

	Passo Fundo		São Borja[a]		Cascavel[a]	
Variety	Sed	FN	Sed	FN	Sed	FN
Triticale BR 1	7	94	4.2	75	6.5	6
OCEPAR 1	5.4	62	4.4	63	5.6	69
CEP 22	6	62	4.5	67	5.7	69
IAPAR 23	4.9	62	3.3	86	4.5	62
PFT 8710	6.2	178	4.9	155	5.4	191
Wheat[b]	8.3	355	7.2	211	11.9	331

[a] The seed from São Borja was provided by Ari Caumo and Danilo Bohn of IPAGRO (Instituto Pesquisas Agronômicas, Rio Grande do Sul). Seed from Cascavel was received from Manoel Bassoi and Francisco Franco of OCEPAR-Pesquisa.

[b] Wheat varieties: CEP 21 in Passo Fundo, BR 32 in São Borja, and IAC 5 in Cascavel.

factors. However, newer varieties such as Arapoti-IAPAR 23 (Hare) have higher yield potentials with improved test weights in these warmer environments.

Irrigated trials in central Brazil and Mato Grosso do Sul State, in some situations, have produced high yields with good test weights comparable, in general, with those of wheat.

A CIMMYT trial at Passo Fundo compared triticale and wheat lines selected for tolerance to soil acidity. The soil was extremely acidic with toxic aluminum toxic (pH 4.6 and 4.25 me of soluble aluminum/dL of soil). Most triticale lines had higher yields, but lower test weights (Table 6), which demonstrates the yield potential of triticale under similar conditions.

Table 5. Yields (kg/ha) and test weights (kg/hl) of triticale and wheat at the Fazenda Itamarati in Ponta Porã and at Planaltina in Brasilia in 1987.

	Planaltina[a]		Ponta Porã[a]			
Altitude (masl):	1007		650			
Latitude:	15°35'		22°12'S			
Mean Temp. (°C):	12		16.5			
	Irrigated		Irrigated		Dryland	
Variety	kg/ha	kg/hl	kg/ha	kg/hl	kg/ha	kg/hl
BR 1	5028	73	1910	70	906	70
OCEPAR 1	3786	69	3195	69	908	70
CEP 22	3959	69	3496	69	1105	69
IAPAR 23	5140	75	3547	74	1220	75
Wheat[b]	4248	74	2756	75	754	74

[a] Data from Planaltina were provided by José Maria Vilela of CPAC/EMBRAPA and from Ponta Porã by Alberto Francisco Boldt and Maria da Graca Fogli, of Fazenda Itamaraty.

[b] Wheat checks: Trigo BR 12 in Planaltina and IAC 24 in Ponta Porã.

Table 6. Yields (kg/ha), test weights (kg/hl), Al^{+++} reactions (Al), and *Helminthosporium* (H) severities of the three (of 10) highest yielding wheat and triticale lines in Passo Fundo in 1983.

Cross/Pedigree	kg/ha	kg/hl	H[a]	Al[a]
Muscox = S-15570-1Y-1B-100B-0Y	2128	68	4	4
Juanillo 97	1946	65	3	4
Sika = B-2683	1658	64	3	5
IAS 58/IAS 55//ALD/3/MRNG/4/ALD/IAS 58//ALD CM55517-B-1F-701Y-1F-707Y-1F-0Y	793	70	2	6
PFT 70354/ALD CM47090-14M-1Y-1F-703Y-10F-705Y-3F-0Y	646	76	2	7
MON/ALD = CM53460-4M-1Y-4Y-0M	387	71	5	7

[a] Scale used: 1 = very tolerant, 9 = very susceptible.

Conclusion and Discussion

Tolerance to mineral stresses—under certain conditions toxic to common wheat varieties—and the efficiency to utilize nutrients are present in many species, including triticale. Breeding triticale for nutritional efficiency and tolerance to mineral toxicities should be considered because the crop appears to have meaningful genetic variability and it is agronomically, economically, and ecologically feasible.

Significant advances have been made in triticale improvement for disease resistance, yield potential, and grain quality. However, little has been consciously done to improve the efficiency of nutrient absorption and tolerance to toxic levels of minerals. Both of these traits exist in rye from where it can be transferred to triticale.

In semi-arid climates, triticale is tolerant to drought, salinity, and boron toxicity, and is very efficient in absorbing copper, zinc, and manganese. Production in the nontraditional, small grain regions in Mexico, Argentina, and Australia demonstrate the crop's potential adaptation.

Triticale's genetic variability for tolerance to toxic levels of Al^{+++}, Fe^{+++}, and Mn^{+++}, its efficiency in utilizing phosphorus on acid soils, and its resistance to disease are factors that encourage the crop's cultivation in nontraditional, warm and humid climates where these problems predominate. The lower incidence of take-all and soilborne viruses, combined with less need for lime and fertilizer use, are positive factors for triticale.

Triticale research in Brazil has stressed the crop's potential as a human food substitute for wheat. However, as the country is developing the capacity for self-sufficiency in wheat, baking quality will have to be improved markedly, or otherwise researchers should probably emphasize triticale's use as feed for poultry, swine and cattle—which represents a huge potential since more than 2 million tons of maize are needed every month and triticale is harvested when maize stocks are low.

In southern Brazil the best adaptation has been demonstrated at altitudes higher than 500 masl. At lower altitudes and under warmer conditions, triticale has not performed well and most institutions have discontinued research in these areas.

For the future, it is important to develop an understanding of the factors responsible for the poorer adaptation of triticale to warmer environments. Helminthosporium in triticale is one of the most important diseases in humid subtropical regions. The disease can be controlled through crop rotation, seed dressing, or fungicide application—and genetically (resistance in triticale has been improved).

Attention should also be devoted to tolerance to mineral toxicity, efficient uptake of nutrients with low availability, and improved tolerance to drought stress. Genotypes with a longer juvenile cycle and improved roots may contribute to more efficient nitrogen use and reduce drought stress.

On soils with higher fertility or on irrigated fields where wheat expresses its yield potential, triticale does not present advantages and there is no evidence that this might change.

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Resumen

El cultivo del triticale (X Triticosecale *Wittmack*; Triticum turgidosecale *[Kiss] MK) se ha difundido con rapidez en muchas regiones del mundo por su mayor resistencia a las enfermedades, su potencial de rendimiento y la mejor calidad de su grano. Este cereal se cultiva extensamente en suelos ácidos y arenosos de las zonas templadas (por ejemplo, Rusia, Polonia y Francia) donde es tradicional el cultivo del centeno. También se cultiva en los ambientes subtropicales semiáridos y húmedos. En las zonas subtropicales húmedas con suelos ácidos, el potencial del triticale se basa en su amplia resistencia a las enfermedades, su alto potencial de rendimiento, su tolerancia a la toxicidad por el aluminio, el manganeso y/o el hierro y su eficiencia en la absorción de fósforo. En regiones semiáridas con problemas de sequía o de salinidad, su adaptación es consecuencia de su tolerancia a la toxicidad por el boro y su eficiencia en el uso del agua, el cobre, el manganeso y el zinc.*

La combinación del potencial de rendimiento y la calidad del grano con la robustez característica del centeno aumenta el potencial del triticale para muchas zonas cálidas donde no es tradicional el cultivo de cereales. En el sur del Brasil, el triticale se ha adaptado muy bien a suelos ácidos situados arriba de los 500 metros sobre el nivel del mar. Con altitudes más bajas o en las zonas de cultivo de secano del centro del Brasil, donde las temperaturas medias durante el macollamiento sobrepasan los 14 °C, el triticale no tiene un buen comportamiento y la mayoría de las instituciones han interrumpido su investigación al respecto.

Effects of Heat Stress on Wheat and Possible Selection Tools for Use in Breeding for Tolerance

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Abstract

This paper examines the major physiological mechanisms affected by high temperatures in wheat at the plant and crop levels and looks at possible selection tools for warm environments.

Increasing maximum soil temperature (5-cm depth) during the germination to emergence phase (E) significantly decreased crop establishment. Crop emergence to double ridges (GS1) and double ridges to anthesis (GS2) decreased in their real time duration with minor changes in degree days by increasing growing temperature. Growth decreased proportionally to mean temperature. Spike number per unit area was affected, in part, as a reflection of poor crop establishment. Grains per spike and spikes per unit area decreased significantly such that the total number of kernels per unit area decreased on average at about 4% for each °C increase in mean temperature over the range of 12.2 to 27.5°C. High temperature tolerance of physiological processes during GS2 could influence the carbon balance of plants when the spike is growing and affect yield components. Evidence is presented indicating that, through field selection, the photosynthesis per unit leaf area at high temperature may be indirectly improved. Lower kernel weight was observed as a result of heat stress during GS3.

Evidence of a relatively constant thermal time for GS1 and GS2 across heat environments is presented, supporting the hypothesis that potential growth at high temperatures could be realized as long as radiation, water, and nutrients are acquired by the plants at a sufficient rate to keep up with the temperature-induced decreased clock time. In practice this implies optimizing agronomy throughout the life of the crop to approach potential growth and increase grain yield.

Based on the physiological responses of the wheat crop to heat stress, traits were identified that may be used in genotype evaluation for increased grain yield in high temperature environments. Simple screening tools and appropriate screening environments are suggested. Present breeders' approaches of the CIMMYT/ICARDA spring wheat breeding program for areas with above-optimum temperatures are presented.

Introduction

Cereal yields are determined by variety, management, and environment. Winter cereals are cool season crops. Among various climatic factors, low water availability and high temperature are major production constraints. These constraints may occur throughout the growing season in the lowland tropics or as terminal stresses affecting the crop during the grain filling period in Mediterranean environments and highlands.

Water and heat stresses are intimately linked through the energy balance of plant organs. One of the important means of dissipating excess net radiation is through latent heat via transpiration,

such that the plant-transpiring surfaces may be several degrees below the ambient temperature. If this energy dissipating mechanism fails due to water shortage, the plant organs exposed to a radiation load will inevitably increase their temperature above ambient, though some compensation in energy dissipation will occur by increased radiation and sensible heat transfer from the heated body.

Recognizing the fundamental linkage between water and heat stresses in plants, we will center our attention on one of them—heat stress—and assume that the wheat plants do not suffer water shortages. It appears that heat and drought affect plants and crop yields differently. For breeding purposes, however, resistance to these two stresses usually has to be combined. The subject appears as highly complex, to the extent that Blum (1988) argued that heat tolerance should evolve in plants that are short in mechanisms of heat avoidance. Transpiration, a mechanism of heat avoidance, is the primary agent for energy dissipation. In other words, a plant that maintains transpirational cooling may have low tolerance and be essentially a heat avoider. In this paper we do not differentiate between heat avoidance and heat tolerance. We are interested in grain yield under heat stress.

Effect of Heat Stress on Wheat

Heat stress decreases total above ground biomass and grain yield in wheat (Table 1). For analysis purposes, and due to physiological plant responses, the development of a winter cereal may be conveniently divided into four major phases:

- Germination to emergence, i.e., crop establishment (E).
- Emergence to double ridges (GS1).
- Double ridges to anthesis (GS2).
- Anthesis to maturity (GS3).

Temperature has a differential effect on each of these phases (Shpiler and Blum 1986, O'Toole and Stockle 1991).

Table 1. Total above ground biomass and grain yield of wheat grown at various mean seasonal temperatures (mean of 24 genotypes).

Environment[a]	Mean seasonal temperature (°C)	Mean temp. at flowering (°C)	Total above ground biomass (g/m^2)	Grain yield (g/m^2)
Normal Mediterranean	12.2	13.0	940.8 a	355.7 a
THS	20.7	17.0	420.9 b	157.3 b
EHS	23.9	27.0	298.4 c	120.3 c
Normal, dry lowland tropic	27.5	25.0	395.0 b	96.0 c

[a] Normal Mediterranean corresponds to Tel Hayda in northern Syria (36°01'N, 36°56'E, 392 m elevation) planted on December 1. Terminal heat stress (THS), planting at Tel Hadya on March 23; early heat stress (EHS), planting at Tel Hadya on July 15; normal, dry lowland tropic; planting at Wad Medani, Sudan (14°23'N, 380 m elevation) on November 15.

Numbers followed by a different letter in a given column differ at $P < 0.05$.

Source: Acevedo and Deifalla, unpubl.

Crop establishment

From sowing to emergence, seedling mortality—and hence crop establishment—is a problem when soil temperatures are high. Plant emergence and population establishment are the starting points of crop growth. The effects of initial stand on wheat crop growth usually diminish with time under optimal growing environments because of compensatory mechanisms such as tillering (Fischer 1985b). In hot environments, however, the maximum soil temperature in the top centimeters may exceed maximum air temperature by 10-15°C if the soil surface is bare and dry and radiation intensity is high. Under such conditions, maximum soil temperature may reach 40 to 45°C with serious effects on seedling emergence. The initial plant population may fall below 100 plants/m^2, considered to be deleterious to crop yield (Midmore 1976). Poor stand establishment may be, in part, due to reduced length of the coleoptile at high temperatures. Decreases in coleoptile length from about 100 mm at 10-15°C to about 30 mm at 35°C have been reported (Burleigh at al. 1964, Kirby 1991). Table 2 shows the average number of wheat plants per unit area established in a nursery of bread wheat genotypes planted at increasing soil temperatures in the field. Significant differences in crop establishment between temperature environments, genotypes, and genotype x environment interactions were found. This provides selection scope for this trait and thus improved wheat crop establishment at above-optimum soil temperatures. Angus et al. (1981) also found that the effect of temperature on emergence varied among wheat genotypes. Furthermore, if seedlings emerge satisfactorily, brief exposures to extreme soil temperature may inhibit crown root growth and tiller initiation (Fischer 1985b).

Table 2. Number of wheat plants established at various soil temperatures (5-cm depth) in the field. The equivalent to 100 kg seed/ha were planted at a depth of 3-4 cm.

Mean maximum soil temperature (°C)	No. of established plants per m^2
20.2	315.3 a
33.7	256.7 b
42.2	89.8 c

Numbers followed by a different letter differ at $P < 0.05$. Source: Acevedo and Deifalla, unpubl.

Emergence to double ridges

The advent of vegetative development and the maximum main tillering stage toward the end of GS1 are coupled to an increased sensitivity to temperature (O'Toole and Stockle 1991). Sensitivity to high temperature during this phase might be expressed as decreased duration of GS1 (Shpiler and Blum 1986) and reduced leaf area development and growth (Table 3). Reduction in total number of leaves and spike bearing tillers has been reported as an effect of high temperature during this phase (Fischer and Maurer 1976, Warrington et al. 1977, Midmore at al. 1984), though compensatory effects due to the decreased number of plants per unit area may occur. Table 4 shows an important decrease in spike number per unit area as temperature increases. This is the result of decreased crop establishment and spike-bearing tillers.

Double ridges to anthesis

The double ridge structure appears in the developing wheat inflorescence about 6 to 7 days after spike initiation (Kirby 1984). This phenomenon marks the beginning of the GS2 growth stage. By the end of this stage, the potential of grain production has been determined (Bagga and Rawson 1977). The GS2 stage is therefore critical in terms of environmental stresses. It appears to be sensitive to temperature stress and notoriously decreases its duration. After GS2, the environmental conditions can only modify the extent to

which the grain yield potential is realized. The main effect of temperature after floral initiation is on the number of kernels per unit area. Previous reports indicate that the number of kernels per unit area decrease at about 4% for each °C increase in mean temperature over the range of 14 to 22°C mean temperature during the 30 days preceding anthesis (Fischer 1985a). A similar value is shown in Table 4 for a mean temperature range from 12.2 to 27.5°C. The effect of temperature on grains per unit area illustrated in Table 4 may be attributed to a decreased number of fertile spikes, to a decreased assimilate supply to the spike, and to an accelerated development rate and hence decreased period for spike growth. Warrington et al. (1977) showed that wheat grown at 25°C during GS2 had only 30 grains in the main ear, whereas plants grown during this period at 15°C had approximately 70 grains in the main spike. Spike dry weight at anthesis is also reduced by higher temperatures and it has been used as a proxy for grain number. Grains per spike in our experiment, however, were not consistently decreased by increased mean growing temperature.

The decrease in duration of GS2 at high temperatures is dependent on genotypic variation in photoperiod sensitivity, vernalization response and optimum temperature for spikelet formation (Blum 1988, Halse and Weir 1970).

Midmore et al. (1984) showed that late cultivars, sensitive to vernalization or photoperiod, produced fewer grains per unit area relative to dry weight at

Table 3. Leaf area index, plant height, and peduncle length as related to growing temperature.

Mean seasonal temperature (°C)	Duration of GS1 (days)	Leaf area index	Plant height (cm)	Peduncle length (cm)
12.2	55.9 a	5.0 a	82.9 a	33.1 a
20.7	22.1 b	2.7 b	57.6 b	24.0 b
23.9	20.4 b	-	48.6 c	20.8 c
27.5	22.2 b	0.9 c	-	-

Numbers followed by a different letter in a given column differ at $P < 0.05$.
Source: Acevedo and Deifalla, unpubl.

Table 4. Some yield components and duration of GS2 at various mean seasonal growing temperatures.

Mean seasonal temperature (°C)	Duration of GS2 (days)	Kernel number (grain/m²)x10²	Spike no. (per m²)	Spike dry weight at anthesis (g/m²)	Spike dry weight at anthesis (mg/spike)
12.2	73.8	91.0 a	349.2 a	187.1 a	535.8
20.7	48.9 b	55.1 b	292.9 b	147.5 b	503.5
23.9	32.4 d	37.6 c	163.2 c	46.2 c	283.1
27.5	38.5 c	35.0 c	145.6 c	111.4 b	-

Numbers in the same column followed by different letters differ at $P < 0.05$.
Source: Acevedo, unpubl.

anthesis. There was a low investment in spike tissue with a high percentage of green tillers at anthesis failing to bear spikes. Day length-sensitive cultivars had small abnormal spikes (Midmore et al. 1982, 1984). However, temperature *per se* appears to have an effect on the reduction of grain number per ear (see Rawson and Bagga 1979).

If genotypes are able to maintain high carbon exchange rates at higher temperatures, the decrease in GS2 duration and spike weight is smaller (Blum 1986). The photosynthetic process is sensitive to heat. The capacity of the chloroplast membranes for electron transport is affected (Berry and Rayson 1981). An increase in chlorophyll fluorescence at temperatures where CO_2 fixation begins to be affected strongly points to heat damage of photosystem II (Seeman et al. 1984). It appears that selection for an improved photosynthetic process is possible when exposing wheat germplasm to heat in the field. Table 5 shows key physiological parameters related to net photosynthesis measured in wheat populations at two successive cycles of selection for heat stress tolerance. A conclusion from these observations is that genotypic variation for adaptation in basic physiological processes, such as net photosynthesis, to high temperature exists, and high temperature tolerance of physiological processes during GS2 could influence the carbon balance of plants when the spike is growing and affect yield components.

Late in GS2, the developing florets contain tissues undergoing gametogenesis. Meiosis is quite temperature sensitive (O'Toole and Stockle 1991). Saini et al. (1983) provided evidence for differential sensitivity of male and female floral components during gametogenesis and the severe sterility that results from the combined responses to water and high-temperature stresses 10 to 15 days prior to anthesis. Results presented by Warrington et al. (1977) also indicated that high temperature reduced grain set by increasing the proportion of large and superficially normal florets that were sterile and did not bear grains.

Table 5. Mean values of net photosynthesis and related variables in experiment A, advanced bread wheat yield trial in its first cycle of selection for heat tolerance, and experiment B, advanced wheat yield trial in its second cycle selection.

Experiment	Leaf temp. (°C)	NP[a] (µmol CO_2/ m^2/S)	TS[a] (mmol H_2O/ m^2/S)	LC[a] (mol/m^2/S)	INT CO_2[a] (µl/L)	TE[a] (mmol CO_2/ mol H_2O)[b]
A	36.2	2.57	5.5	0.118	242.6	0.47 (2.46)
B	34.8	6.00	6.6	0.174	205.6	0.91 (3.81)
B-A	-1.4	3.43	1.1	0.056	-37.0	0.44
LSD (0.05)	0.6	1.28	0.7	0.022	14.1	

[a] NP = net photosynthesis; TS = transpiration; LC = leaf conductance; INT CO_2 = internal CO_2; TE = transpiration efficiency.

[b] The saturation deficit for experiment A was 5.2 KPa and for experiment B 4.2 KPa. The values in parentheses are the product of the saturation deficit times TE.

Source: E. Acevedo, unpubl.

Anthesis to maturity

Heat stress during GS3 affects mainly assimilate availability, translocation of photosynthates to the grain, and starch synthesis and deposition in the developing grain. The net result of heat stress at this stage is lower kernel weight. Studies of Wardlaw et al. (1980), Wiegand and Cuellar (1981), and others show that, over the range of a 12 to 26°C increase in mean temperature during grain filling, grain weight is reduced from 4 to 8% per degree increase in temperature, on the average. Table 6 shows an average reduction of 4% in grain weight per °C increase in mean air temperature during grain filling.

Lower grain weight is believed to result from the combined effects of the duration and rate of the grain filling process. Decreased duration would decrease final grain weight unless offset by an increase in the rate of grain filling. Sofield et al. (1977) showed that a temperature increase from 15/10°C to 21/16°C (day/night) would reduce the duration of grain filling from 60 to 36 days. The kernel growth rate increased, however, from 1.49 to 3.03 mg/kernel per day, thus compensating for the reduced duration. The duration in grain growth decreased further from 36 to 22 days with an increase in the temperature regime from 21/16°C to 30/25°C. No increase in the rate of dry matter accumulation in the grains in the latter case was observed. Table 6 shows our results, which indicate that, in spite of increased mean crop growth temperatures and grain filling temperatures, the mean grain filling duration for 24 wheat genotypes was similar—yet the grain weight decreased substantially. This indicates a decrease of the mean grain filling rate with increased temperature, on average, for the genotypes tested.

An Analytical Tool for Studies on Heat Stress Tolerance

The identification of genotypic traits that are potentially beneficial in counteracting a given environmental stress, such as heat, usually poses a problem. Analytical tools should help in integrating and quantifying concepts as well as for formulating hypotheses.

In the previous section, we briefly reviewed some aspects of crop response to temperature stress. Our aim in this section is to identify physiologically based traits that can be used in genotype evaluations. Remember that, although plant responses to temperature are usually related to air temperature, they

Table 6. Grain filling duration and final grain weight of wheat grown at four temperatures (mean of 24 genotypes).

Crop growth mean temperature (°C)	Grain filling mean temperature (°C)	Grain filling duration (days)	Final grain wgt. (mg)	Grain filling (mg/kernel per day)
12.2	17.0	28.5 a	39.5 a	1.39
20.7	24.0	29.4 a	28.9 b	0.98
23.9	25.6	26.5 a	30.5 b	1.15
27.5	24.4	30.5 a	27.6 c	0.91

Numbers in a column followed by a different letter differ at $P < 0.05$.

are, in fact, related to the temperature of the tissues and organs involved. This temperature fluctuates diurnally, seasonally, and spacially in a crop and is determined by the water and energy balance of the soil-plant-atmosphere system.

As already shown, the sensitivity of wheat plant organs to high temperatures varies with the growth stage. Table 7 summarizes the major wheat growth stages along with the most significant physiologic/agronomic events occurring within each stage. High temperatures have the effect of chronologically accelerating development and shortening the various growth stages, usually negatively affecting crop establishment, leaf area development, ground cover by the crop, radiation interception, and photosynthesis per unit ground area. These, in turn, have an effect on the crop parameters directly related to wheat yield, such as spike number per unit area, potential number of spikelets per spike, spike weight at anthesis, potential grain number, and individual grain weight. Which of these is affected at a given time depends on its prevailing predominance as a sink for assimilates. Figure 1 summarizes the effects of high temperatures on growth development and yield.

All those factors and agronomic practices that would increase stand establishment and growth, or else decrease development rate, would appear to favor grain yield at high temperatures. Escape mechanisms, such as choosing a planting date that would cause anthesis to occur during the coolest growing month in warm environments (Fischer 1985b), would undoubtly help achieve high yields, as it would in having genotypes that maintain a lower temperature either by high transpiration rates and/or reflective properties of the canopy (e.g., glaucousness of stems, leaves, and

Table 7. Wheat growth stage and significant physiological/agronomic events affecting grain yield.

Growth Stage	Agronomic/Physiological Event
Germination-emergence (E)	Crop establishment.
Emergence-double ridges (GS1)	Leaf number, leaf area, tiller number, groundcover, radiation interception, photosynthesis/ground area.
Double ridges-terminal spikelet (GS2)	Leaf area, groundcover, radiation interception, photosynthesis/ground area, potential number of spikelets. Spike number.
Terminal spikelet-anthesis (GS2)	Leaf area, ground cover, radiation interception, photosynthesis/ground area, spike growth, potential grain number. Spike number.
Anthesis-yellow spike (GS3)	Radiation interception, photosynthesis/ground area, realized grain number, grain filling.

spikes—Johnson et al. 1983). Genetic variability has been observed in most of the traits listed in (or related to) Figure 1 (Table 8).

Actual duration of development under high temperature conditions is critical to wheat yield. Midmore et al. (1982, 1984) have indicated three mechanisms by which longer duration can come about:

- Vernalization sensitivity.
- Photoperiod sensitivity.
- Pre-anthesis duration in cultivars insensitive to vernalization and photoperiod.

But as already mentioned, partitioning of dry weight to the spike may be poor in photoperiod- and/or vernalization-

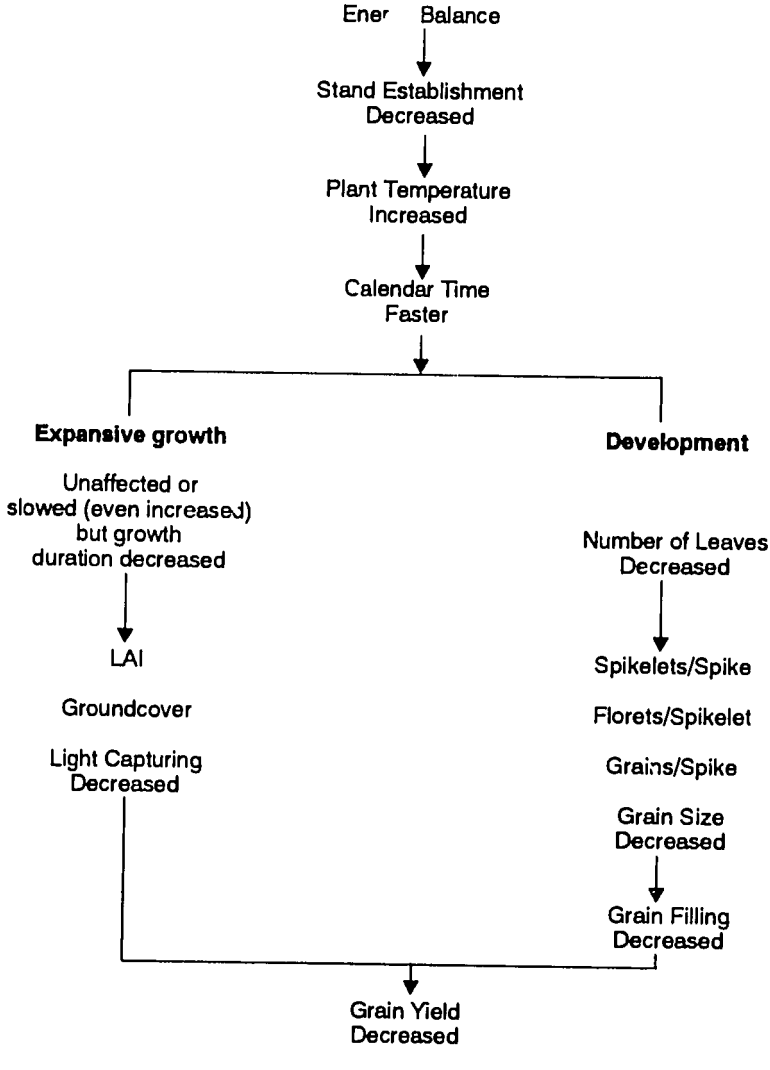

Figure 1. Effects of high temperatures on wheat growth, development, and yield.

responsive genotypes grown in warm, short-day environments. They had a high percentage of green tillers that failed to bear spikes (Midmore et al. 1984).

Actual grain weight is usually below potential because of decreased grain filling duration and inadequate grain filling rate compensation. Potential grain weight is usually reduced when mean air temperatures are above 18°C, but genetic variability may exist (Wardlaw et al. 1989).

Table 9 summarizes the working hypothesis for identifying traits that produce genotypes with tolerance to heat stress. To test such traits experimentally, a study nursery must be assembled that has a set of genotypes that represent variability in the postulated traits. The worth of the traits can be assessed by the extent of their correlation with grain yield in the appropriate screening environment (Table 9). Eventually, to demonstrate that the traits contribute to heat stress tolerance, appropriate crosses and divergent selection experiments must be done (Acevedo and Ceccarelli 1989).

Simulation models can complement the assessment of traits. O'Toole and Stockle (1991) recently used this methodology to analyze two temperature-related traits—root growth and grain filling. Their results show that, if genotypes are found with an optimum soil temperature for root growth that matches the prevailing soil temperature, significant increases in wheat grain yield can be obtained. Similarly, if a plateau in grain filling rate in a genotype occurs at 18°C, the grain filling duration would be the limiting factor if the genotype is grown at 26°C, resulting in a significant yield decrease.

Toward Explaining Decreased Grain Yield at High Temperatures

Grain yield consists of grain number per unit area and individual grain weight. Maximizing these two components for a given environment maximizes grain yield.

Rawson (1988) noted that high temperature has minimal effects on plant time, as measured in degree days (°CD), above a given threshold temperature. Indeed, Table 10 shows that a wheat nursery grown in five temperature field environments presented, on the average of 24 entries, relatively constant thermal times for two of three recognized growth stages (GS1: emergence to double ridges and GS2: double ridges to anthesis). Clear

Table 8. Genetic variability in traits related to wheat growth and development at high temperatures.

Emergence at high temperatures	Angus (1981), Acevedo and Deifalla, unpublished
Optimum temperature during spikelet formation	Halse and Weir (1979)
CER at high temperatures	Blum (1986)
GS2 duration at high temperature	Shpiler and Blum (1986)
Photosynthate partitioning to the spike	Fischer (1985a)
Glaucousness of the aerial organs	Johnson et al. (1983)
Vernalization sensitivity	Midmore et al. (1982, 1984)
Photoperiod sensitivity	Midmore et al. (1982, 1984)
Weight per grain	Wardlaw et al. (1989)

differences in °CD were observed only in GS3, anthesis to maturity. This growth stage may have been affected by temperature and drought, particularly at the normal planting date, terminating after a similar calendar time in all environments.

If thermal time is constant, high temperature may have little effect on the potential number of organs produced by the plant for a given genotype and photoperiod, as long as growth resources of radiation, water, and nutrients are acquired by the plants at a rate that satisfies potential growth (Rawson 1988). The rate of acquisition of resources may have to increase substantially for this to occur since the calendar time required to complete each growth stage is decreased significantly with increase in temperature (Table 10). According to this hypothesis, if growth resources are not supplied at the rate demanded by the increased temperature, the size of the organs is reduced. In theory, growth resources could be manipulated at any stage of plant time to affect an appropriate yield component. In practice, this implies optimization of agronomy throughout the life of the crop.

If temperature per se has relatively little effect on the rate of photosynthesis per unit leaf area, carbohydrate accumulation would be directly proportional to hours and intensity of sunlight and area of leaf intercepting radiation when a crop is growing under unlimited input conditions.

It should be possible to manipulate inputs at each stage of growth to control the size

Table 9. Physiological/morphological traits of plants and crops of potential usefulness as screening tools for high-temperature stress.

Development stage	Trait	Screening tool	Screening environment
Emergence	• Crop establishment	• Plant No./m^2 • Early heat stress	• Growth chamber
Five-leaf stage in the main shoot (Zadoks 15-23, double ridges)	• Crop growth • Radiation interception and photosynthesis/ ground area • Long E-DR period • Profuse root system	• Visual • Cover and vigor scores • Days to DR (5 leaves) • Low canopy temperature	• Early heat stress • Heat stress throughout
Anthesis	• Low vernalization • Timing of anthesis (coolest month) • Radiation interception • Potential grain number • Stability of GS2	• Days to anthesis • Ground cover • Spike dry weight • Duration DR-anthesis	• Early heat stress • Heat stress throughout • Terminal heat stress
Yellow spike	• Photosynthesis/area • Grain filling duration • Grain filling rate • Grain weight • Good partitioning	• Stay green • Maturity-anthesis (days) • GW/maturity-anthesis (days) • 1000-kernel weight • Harvest index	• Terminal heat stress • Heat stress throughout

of each organ. In fact, Fischer (1985a) indicated that kernel number (or spike dry weight used as a proxy) would be maximum under nonwater limiting conditions if sufficient leaf area to fully cover the ground had developed by the terminal spikelet stage or the beginning of spike growth, a high photosynthetic rate were maintained during spike growth, and enough phothosynthates were partitioned to the growing spike. The amount of photosynthates available would depend essentially on radiation and temperature during the spike growth period, the first fixing the rate of photosynthesis, while the second would fix the length of the spike growth period and hence the number of viable florets and potential grain. Considering these two major environmental factors in a ratio called the photothermal quotient, PTQ, which =

$$\frac{\text{mean solar radiation}}{\text{mean temperature -4.5}}$$

in a period of 20-30 days preceding anthesis, Fischer (1985b) predicted grain number relatively well, particularly when correcting PTQ for incomplete radiation interception. The PTQ integrated the positive and linear effects of radiation on crop growth rate and mean temperature on development rate.

The PTQ between terminal spikelet and heading at high temperature accounted for 92% of the variation in yield observed by Rawson (1988) under controlled environment conditions. It also predicted well data obtained by other scientists. Fischer (1985b) also suggested that grain weight was essentially a function of temperature during the grain filling period (30 to 40 days following anthesis).

Table 11 shows the relative sensitivity of various relevant physiological processes to heat stress. The central question, however, is: can present physiologic understanding of wheat behavior under

Table 10. Duration of various growth stages in wheat as a function of mean growing temperature during the stage.

Treatment (environment)	Growth stage	Mean growing temp. during period (°C)	Growth stage duration (days)		(°CD)	
Normal	GS1	8.4	56	a	459	a
	GS2	10.3	74	a	827	ab
	GS3	17.0	29	a	606	c
THS	GS1	14.2	-		-	
	GS2	17.2	49	b	883	ab
	GS3	24.0	29	a	770	b
HS	GS1	23.4	22	b	513	a
	GS2	27.1	29	d	782	b
	GS3	31.2	29	a	894	a
EHS	GS1	31.3	20	b	576	a
	GS2	28.6	32	d	893	ab
	GS3	25.6	27	a	586	c
Medani	GS1	27.2	22	b	562	a
	GS2	24.6	39	c	938	a
	GS3	24.4	31	a	748	b

For each growth stage, numbers followed by the same letter do not differ at $P < 0.05$.

heat stress help in improving grain yield and the efficiency of selection for grain yield in a hot target environment? Some simple considerations appear relevant:

- In hot environments, the wheat crop should reach anthesis during the coolest month.
- Full ground cover, and hence high light interception, should be attained early in the season—ideally 1 month before anthesis. Good agronomic management and an appropriate genotype should assure this requirement. Genotypic effects, such as fast leaf emergence (reduced phyllochron interval) and increased number of tillers, are also desirable. The terminal spikelet to anthesis period should coincide with a high LAI and peak PTQ.
- Some vernalization requirement may prolong the vegetative period and increase radiation interception in the early growth stages.
- High transpiration cooling may avoid heat stress by lowering the canopy temperature (See Fischer and Byerlee 1991).
- Improved energy balance of heated organs via organ glaucousness appears desirable.
- A longer grain filling period may help to maintain grain weight under heat stress.
- A deep root system may help avoid heat if there is moisture stored deep in the soil profile.

Selection Procedures and Criteria Presently Used by the CIMMYT/ICARDA Spring Wheat Project to Identify Heat-Resistant Genotypes

It appears that there is enough evidence (Buddenhagen 1983, Boyer 1982, Blum 1988) to indicate that breeding material has to be exposed to the environmental

Table 11. Relative sensitivity of various physiological processes to heat stress.

Physiological process	Sensitivity to high-temperature stress
Germination to emergence	Medium
Crown root growth	Medium
Number of leaves in the main shoot	High
Tiller initiation	Medium-High
Number of grains/spike	Medium-High
Photosynthesis (20-35°C)	Low
Photosynthesis (>40°C)	High
Maintenance respiration	High
Green leaf area production	Medium
Relative growth rate (12-35°C)	Low-Medium
Individual grain weight	High

stresses of concern in order to identify the genotypes that present a better adaptation. The complexity of the processes affected by physical stresses and the variability of the incidence of the stresses is such that it is almost impossible to fully mimic the stress environments and their effects on physiological processes by using controlled environments and/or laboratory tests. As explained, heat stress at various stages of development in cereal crops, and particularly in wheat, does have a differential effect on crop growth and development—and hence yield.

From the above, three major conclusions may be drawn:

- Presently, the selection procedure from a breeding standpoint has to be essentially based on field-grown plants.
- The breeding material has to be exposed to heat stress at various stages of development.
- The final proof of stress resistance is obtained in the target environment.

The CIMMYT/ICARDA spring wheat breeding program is serving areas with above-optimum temperatures for wheat growth during the whole season, like the Sudan and certain areas of Egypt. It is also producing wheat genotypes for North Africa and West Asia where Mediterranean climate types predominate. These climates are characterized by above-optimum temperatures occurring together with terminal drought during the grain filling period.

Some traits related to high temperature stresses can be screened in early generations by visual selection. These include floret sterility, premature leaf senescence, leaf firing, maturity class, and grain shriveling. Yield testing can not be done until a more advanced generation is reached. In order to generate suitable material for use in breeding programs representing various heat environments, a differential planting procedure has been implemented (Nachit and Ketata 1991). By advancing or deferring planting, heat stress along with other environmental stresses occur when the germplasm is at its critical stages of development. Figure 2 presents the general pattern of the differential planting strategy and shows the values of 84 bread wheat advanced lines grown in the 1988-89 season under three stress environments. The plantings were done in northern Syria and include normal planting (NP) on November 15, early planting (EP) on October 1, and late planting (LP) by the end of March. The EP used, along with supplementary irrigation, allows for low temperature screening. The NP in environments of less than 250 mm winter rainfall permits terminal drought screening, while the LP with supplementary irrigation submits the plants to terminal heat. Figure 2 also shows the heading and maturity dates for the nurseries along with major climatic variables. The resistances to these stresses have to be combined in genotypes targeted to Mediterranean environments characterized by low winter temperatures and terminal drought and heat stresses (Nachit and Ketata 1991).

Figure 3 shows the air temperatures at Tel Hadya in northern Syria and Wad Medani in Sudan. Heat stress at Tel Hadya during grain filling mimics the Sudan situation at this growth stage. A summer planting (15 June) at Tel Hadya exposes the breeding material to early heat stress (EHS), during the germination to emergence, vegetative, floral induction, and spike development periods. This screening complements the LP and late heat stress for the dry lowland tropics (Figure 4).

Breeding material combining tolerance to terminal heat stress and early heat stress is distributed to national programs where

these stresses are prevalent. An example of this type of environment is found in Wad Medani where heat stress occurs throughout the season. The insensitivity to photoperiod is ensured by selecting under short days (Wad Medani, 14°24'N, 380 masl) and long days at Tel Hadya. The genotypes are also grown at 12- and 15-h day lengths in greenhouses at Tel Hadya. Table 12 shows the top four yielding entries in the Regional Heat Tolerance Yield Trial of the CIMMYT/ICARDA Program, grown at Wad Medani under the extreme heat stress conditions of the 1988 season. These lines were 8 to 14% higher yielding than the national check, Debeira; two lines yielded statistically higher than the national and improved checks.

Correlations between physiologic/agronomic traits in the high yielding material selected at Tel Hadya and grain yield (Table 13) (also see Nachit and Ketata 1991) indicate that seedling vigor (early growth), number of fertile tillers, spike fertility, and maturity class are useful complementary traits in selecting for early and late heat stress. Days to emergence is an important selection criterion when early heat stress occurs. The information obtained by breeders is coincidental to the physiological reasoning (and evidence) that heat stress before heading is most deleterious to grain yield in dry lowland tropics.

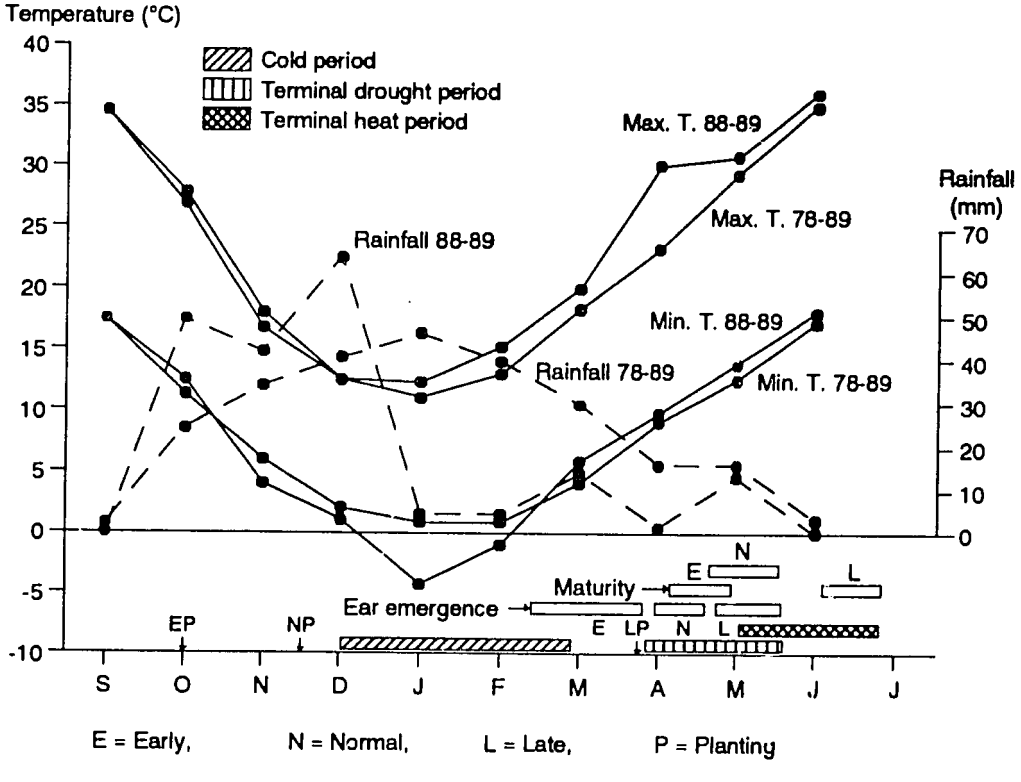

Figure 2. Phenological development of bread wheat germplasm under three stress environments. Source: Ortiz Ferrara et al. (1990)

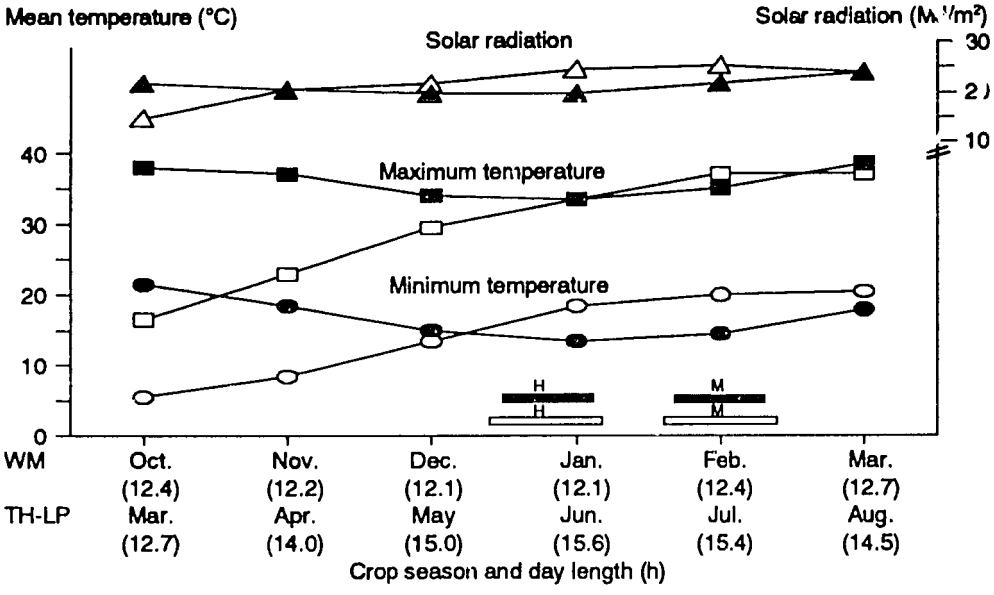

Figure 3. Long-term (1974-1984) mean monthly solar radiation, maximum and minimum temperature, and daylength of the wheat growing seasons in Wad Medani, Sudan (WM, solid symbols), and Tel Hadya—late planting (TH-LP, open symbols). H and M indicate ranges of heading and maturity. Adapted from: Ortiz Ferrara et al. (1991).

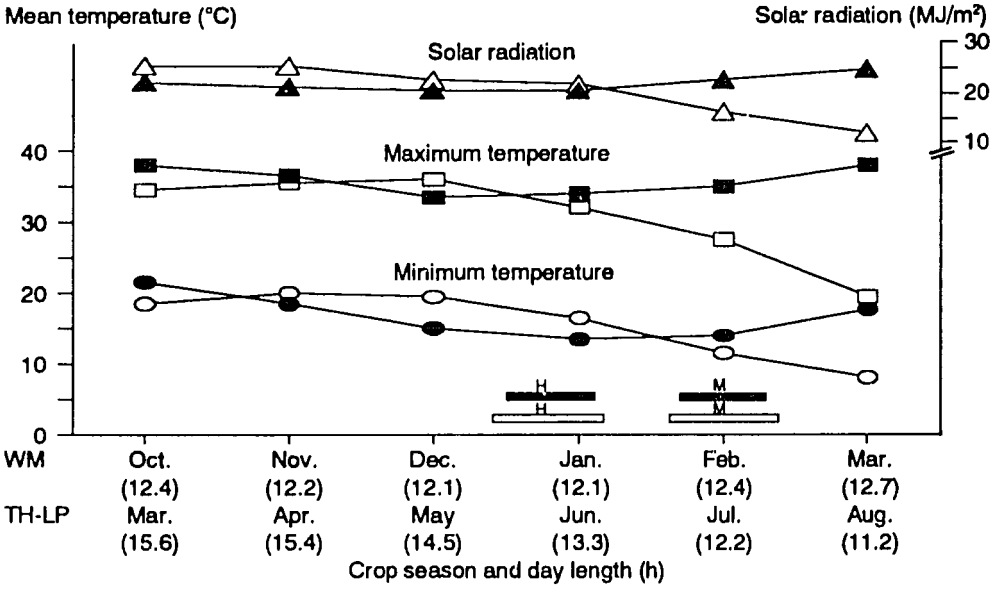

Figure 4. Long-term (1974-1984) mean monthly solar radiation, maximum and minimum temperature, and day length for the wheat growing seasons in Wad Medani, Sudan (WM, solid symbols), and Tel Hayda—summer planting (THS, open symbols). H and M indicate ranges of heading and maturity. Adapted from: Ortiz Ferrara et al. (1991).

Laboratory-Measured Traits: Their Relation to Field Performance of Wheat Under Above-Optimal Temperatures

It is clear that there are not only direct deleterious effects of heat on physiological processes related to photosynthesis, respiration, and reproduction, such as flower abscission, pollen sterility, and poor fruit set, but as shown, plant phenology is distinctly affected by heat. Phenological events are accelerated by the cumulative effect of temperature. The acceleration of plant processes may affect yield by causing a reduction in plant organ size. These responses, in turn, are not straight forward, but are modified by photoperiod and vernalization requirements. Short days, prevailing at low latitudes, delay the onset of spikelet initiation and prolong its duration in photoperiod-sensitive genotypes. Genotype vernalization requirements may also delay flowering at low latitudes. All possible combinations of photoperiod and vernalization requirements may be found in wheat (Midmore et al. 1982). The process of heat stress acclimation is another complicating factor. The evaluation to heat resistance needs to consider various levels of plant organization as well as the interaction of time x temperature x physiological processes.

In laboratory tests of heat resistance, a brief exposure to a heat shock is often used (Oneoueme 1979, Blum 1988). The question is whether plant response to a controlled, brief heat shock is predictive of its response to moderately high temperatures for an extended period of time (Blum 1988) because, in heat resistance breeding, long-term exposure to sublethal high temperatures is important.

With the above views in mind, it has been recognized, however, that membrane stability at high temperatures is important to heat tolerance. Heat damage to the plasma membrane can be estimated by conductometric measurements of solute leakage (Sullivan et al. 1977). Furthermore, heat damage to the

Table 12. Performance of bread wheat germplasm under extreme heat stress conditions in Wad Medani, Sudan. Regional heat tolerance yield trial (RHYT) 1987-88.

Cross and Pedigree	Yield (kg/ha)	% of national check	Heading (days)	Maturity (days)
HI 669/VEE'S' CM 62553-1A-1AP-2AP-0AP	1458	114	49	93
CLEMENT/ALD'S' SWM 09813-5Y-2Y-0Y-3AP-0AP	1433	112	56	86
TOW'S'/PEW'S' CM59443-4AP-1AP-4AP-AP-0AP	1383	108	53	92
VEE'S'/TSI'S' CM 58943-1AP-1AP-2AP-0AP	1383	108	51	95
GENARO 81 (Improved Check)	1116	88	54	98
DEBEIRA (National Check)	1275	100	49	93
LSD 0.05	148			
CV (%)	16			

chloroplasts can be assessed by photosynthesis and chlorophyll fluorescence.

Blum (1988) concluded on this subject that "cell membrane thermostability is a fair index of genetic variation in heat tolerance that bears a reasonable relationship to plant performance under heat stress." The advantage is that these methods are rapid and the whole plant need not be sacrificed. The principle dates back to 1864 (Sacks 1864, cited by Oneoueme 1979). The method has recently been used successfully to separate heat tolerant genotypes of spring wheat similar in plant height and maturity in areas where heat stress occurs during grain filling such as the southern part of the northern Great Plains of the USA (Shanahan et al. 1990). It would appear that, once highly adapted material has been found for a given high temperature stress environment, the membrane stability test may aid in selection for heat stress tolerance.

Other laboratory measured traits like photoperiod and vernalization requirements are obviously an important complement to developing adapted heat tolerant genotypes.

Conclusions

The knowledge and understanding of wheat growth and development in environments with above-optimum temperatures have increased substantially in the last decade. Appropriate genotypic traits, other than grain yield, for various development stages have been identified. Simple screening tools are at hand as long as the genetic material is grown in the appropriate environments.

At present, it is recognized that different heat stress environments exist and that a different kind of germplasm should fit these environments.

Plant breeders should benefit by using the concepts and screening tools described in this paper. Assessment of these tools

Table 13. Correlation coefficient between grain yield and seven agronomic characters under terminal (THS) and early heat stress (EHS) conditions, Tel Hadya, Syria, 1985 and 1986.

Agronomic Characters	Correlation Coefficients		
	THS-1985	THS-1986	EHS-1986
Days to emergence	0.03	0.08	-0.27**
Seedling vigor	0.12	0.23**	0.34**
Days to heading	-0.28**	-0.32**	-0.61***
Days to maturity	-0.25**	-0.23**	-0.72***
No. of fertile tillers	0.62***	0.63**	0.37**
Spike fertility	0.43**	0.32**	0.65**
Plant height	0.13	0.28**	0.14

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.
Adapted from: Ortiz Ferrara et al. (1990).

would undoubtly speed up their validation and so plant and crop physiologists are invited to test these hypotheses. Hard evidence to validate these hypotheses should be convincingly produced through indirect divergent selection experiments for each trait and/or combination of traits and comparing them with selection efficiency when yield alone is used.

Many of the traits considered at the crop level can be manipulated agronomically in locally adapted germplasm. Perhaps the quickest and most fundamental advances in yield in the nontraditional, warm areas could be done in this way. The necessary elements have been presented in this paper.

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Resumen

Este trabajo examina los principales mecanismos fisiológicos del trigo afectados por las temperaturas elevadas a nivel de las plantas y del cultivo y considera posibles instrumentos de selección para obtener tolerancia a los ambientes cálidos.

El incrementar la máxima temperatura del suelo (5 cm de profundidad) desde la germinación hasta la emergencia (E) redujo en forma significativa el establecimiento del cultivo. El período entre la emergencia del cultivo hasta la etapa de dos bordes (GS1) y desde esta última etapa hasta la antesis (GS2) disminuyó en cuanto a la

duración real, con alteraciones menores en los días grado por la cada vez mayor temperatura de desarrollo. El crecimiento disminuyó en forma proporcional a la temperatura media. El número de espigas por unidad de superficie fue afectado, en parte, como resultado del establecimiento deficiente del cultivo. Los granos por espiga y las espigas por unidad de superficie disminuyeron significativamente, de tal modo que el número total de granos por unidad de superficie se redujo en promedio un 4% por cada grado de aumento en la temperatura media por encima de 12.2-27.5 °C. La tolerancia a las temperaturas elevadas mostrada por los procesos fisiológicos durante la GS2 podría influir en el balance de carbono de las plantas cuando la espiga está creciendo y afectar los componentes del rendimiento. Se presentan datos que indican que, mediante la selección en el campo, se puede mejorar en forma indirecta la fotosíntesis por unidad de superficie foliar a una temperatura elevada. Se observó un menor peso de los granos como resultado del calor excesivo durante la GS3.

Se presentan pruebas de un tiempo térmico relativamente constante para la GS1 y la GS2 en todos los ambientes cálidos, que apoyan la hipótesis de que podría lograrse el desarrollo potencial a temperaturas elevadas siempre que las plantas reciban la radiación, el agua y los nutrimentos en una cantidad suficiente para compensar la reducción en el tiempo físico inducida por la temperatura. En la práctica, esto implica optimar la agronomía durante la vida del cultivo para aproximarse al desarrollo potencial y aumentar el rendimiento de granos.

Sobre la base de las respuestas fisiológicas del cultivo de trigo al calor excesivo, se identificaron características que pueden usarse en la evaluación de genotipos para obtener un mayor rendimiento de granos en ambientes con temperaturas elevadas. Se proponen instrumentos sencillos de selección y ambientes apropiados para ésta. Se presentan los métodos usados en la actualidad en el programa de mejoramiento de trigo de primavera del CIMMYT/ICARDA para las zonas con temperaturas superiores a las óptimas.

Overcoming Salt Stress through Breeding for Tolerance

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Abstract

Reclaiming soils affected by salt to the point where sensitive crops can be productive requires substantial time and investment. A less costly alternative in the long term is to breed tolerant crops that are productive on such soils or partially reclaimed ones. Salt tolerance breeding is not a long-term substitute for water management, but could be an important contribution to improve yields in coastal areas and areas where salinity has occurred due to poor irrigation system design or management. In view of the observed distinct inter-varietal differences regarding tolerance to saline and alkaline soil conditions, it has been concluded that breeding varieties suited to salt-affected soils appears to be promising in the cases of hexaploid wheat and rice. There is, however, an urgent need to develop simple, efficient, and nondestructive selection criteria for this purpose. It is also suggested that planned and more vigorous efforts should be directed toward systematic collection and critical evaluation of indigenous cultivars of different crops from salt-affected areas to provide a wide range of genetic variability for both basic studies as well as breeding programs.

Introduction

In many agricultural areas, farmers face the problem of producing crops on soils that are not conducive to good crop growth because they are affected by salinity. Salinity problems frequently occur in irrigated areas where salts from saline waters accumulate or because water resources are poorly managed allowing salts to accumulate in the surface layer where seeds germinate and develop roots. Farmers usually become concerned with this situation only when crop yields are affected. Salt can also be a problem in low rainfall areas.

Since the processes that create salt toxicity are continuous and may even accelerate to the point where soils will be completely unsuitable for growing crops, the development of tolerant genotypes cannot be expected to be a permanent solution. Experimental results indicate that different crops vary in their general ability to perform under salt stress conditions (Tables 1 and 2). It is evident that the more salt tolerant a species is, the longer the process of salt accumulation will continue. In such a situation, plant breeders could be effective for a while by developing varieties of species that tolerate even higher salt levels. However, this would only delay the inevitable—the inability of the soil to support crops with even high degrees of salt tolerance. A more realistic role for plant breeders is to develop crop varieties for use during reclamation of problem areas.

Germplasm Collection and Evaluation

The quest for salt-tolerant germplasm is a very recent development and a more extensive search for sources of suitable germplasm must be made. Germplasm of crop plants has considerable genetic plasticity (Shannon 1978) and the importance of collecting and utilizing germplasm has been generally recognized (Frankel 1970, Konzak and Dietz 1969, Krull and Borlaug 1970, Holocomb et al. 1977). Modern varieties have a relatively narrow genetic base and are poorly

adapted to adverse environments such as salinity (Manning 1955). However, endemic genotypes from problem environments may provide the basic germplasm for breeding salt-tolerant varieties with acceptable yield potentials (Frankel 1970, Kingsbury and Epstein 1984, Singh and Rana 1985, Rana 1986, Mishra and Bhattacharyya 1987).

Genetic resources collected as population samples of specific stress environments should be maintained as populations without the loss of their genetic integrity. In this context, the environment where the genetic resources are to be rejuvenated should provide equal opportunities for all seeds to grow and produce progeny, otherwise genetic drift may occur due to poor performance of a certain proportion of the population. Thus, optimum environments in terms of the particular stress should be defined for the rejuvenation of germplasm collections.

The measurement and classification of the genetic potential of a species or collections within a species, with respect to adaptability to a particular soil condition(s), should enable plant breeders to select for particular characters in relation to the soil stress. This could be done by testing the growth of the material in diversely stressed environments. However, testing in different environments is expensive and time consuming and the testing in one stress environment may not be representative of the entire stressed area, which may vary considerably within its geographic domain. Nevertheless, if a soil scientist could describe precisely what is causing

Table 1. Threshold soil electrical conductivity extract (ECe) values of selected crops and ECe values at which there is a 50% yield reduction.

Crops		Threshold salinity levels (ECe in dS/m)	50% yield reduction
Field crops			
Barley	*Hordeum vulgare*	8.0	17.5
Sugarbeet	*Beta vulgaris*	7.0	16.0
Cotton	*Gossypium hirsutum*	7.7	16.0
Safflower	*Carthamus tinctorius*	6.5	14.0
Wheat	*Triticum aestivum*	6.0	14.0
Rice	*Oryza sativa*	3.0	8.0
Maize	*Zea mays*	1.7	7.0
Beans	*Phaseolus vulgaris*	1.0	3.0
Vegetables crops			
Spinach	*Spinacia oleracea*	2.0	8.0
Tomato	*Lycopersicon esculentum*	2.5	8.0
Cabbage	*Brassica oleracea* var. capitata	1.8	7.0
Potato	*Solanuam tuberosum*	1.7	6.0
Onion	*Alium cepa*	1.2	4.0
Carrot	*Daucus carota*	1.0	4.2
Forages			
Alfalfa	*Medicago sativa*	2.0	8.2
Clovers, alsike and red	*Trifolium* spp.	1.5	4.2

the stress in terms of salinity, pH, and mineral toxicity or deficiency, the soil stress could be then duplicated under controlled laboratory conditions. Thus, various levels and combinations can be experimentally constructed and the genetic resources can be tested under the appropriate conditions where other environmental variables are minimized. This approach defines more precisely the interaction of the genetic resources with specific stress environments. Thus, genetic resources can be compared with reference to specific stress environments.

The catalog on the relative performance of genetic resources of specific crops should include information on standard check varieties. In addition, a standard set of minimal descriptors and screening procedures should be defined and agreed upon among the institutes working on specific crops under specific soil stresses. This will allow data at the national and international levels to be compared. The data should be properly documented and inputted into computer systems that allow easy retrieval of the information.

Table 2. Threshold exchangeable sodium percentage (ESP_t), slope, and the ESP value at which yield is reduced by 50% (ESP_{50}) of crops for medium-textured soils (sandy loam).

Crop		Piecewise linear model		
		ESP_t[a] (%)	Slope	ESP_{50}[b] (%)
Barley	*Hordeum vulgare*	8.5	3.5	22.3
	Pot study	13.5	9.1	19.0
Cowpea	*Vigna unguiculata*	9.0	3.0	25.7
Sesbania	*Sesbania aculeata*	46.9	2.4	67.7
Gram	*Cicer arietinum*	7.7	5.0	17.7
Goundnut	*Arachis hypogaea*	8.0	2.2	29.7
Guar	*Cyamposis psoralodes*	11.9	3.2	27.5
Lentil	*Lens esculentum*	4.9	5.5	14.0
Lineseed	*Linum usitatissimun* L.	13.3	2.3	25.0
Pearlmillet	*Pennisetum typhoideum*	13.6	2.6	32.8
Raya	*Brassica juncea* L.	7.6	0.8	70.1
Rice	*Oryza sativa*	24.4	0.9	80.0
	Pot study	32.7	1.3	71.2
Rye	*Secale cereale*	11.0	2.6	30.2
Sesamum	*Sesamum indicum*	9.0	3.6	22.8
Soybean	*Glycine max*	8.0	3.5	22.3
Sunflower	*Helianthus annus* L.	11.3	1.1	56.8
Safflower	*Carthamus tinctorius*	7.6	5.2	17.2
Bread wheat	*Triticum aestivum*	16.4	2.1	40.2
	Pot study	20.4	2.6	39.6
Pea	*Pisum sativum*	7.7	4.1	19.9
Onion	*Allium cepa*	9.8	2.2	32.5
Garlic	*Allium sativum*	9.5	1.8	37.3

[a] ESP values indicate average soil ESP of the 0 to 15-cm layer.
[b] ESP value at which yield is reduced by 50%.
Source: Gupta and Sharma (1990).

Breeding for Tolerance to Salt Stress

The challenging job of genetically modifying plants for better adaptation to saline soils is being actively pursued at the Central Soil Salinity Research Institute (CSSRI), Karnal, India. The effort is interdisciplinary where classical genetics is applied in combination with modern techniques. Figure 1 outlines the integrated approach. Plant physiologists and breeders working together can create conditions that will enable the identification of parental breeding stocks. Salinity basins or microplots can be created for crops like rice, wheat, and barley. Water containing salts is added to adjust and maintain the electrical conductivity (EC) at the desired level. Alternatively, the basin/plot can be filled with artificially prepared soil to simulate the desired stress. The size of the plot should be such that the desired level of salinity or sodicity can be maintained easily and the soil is uniform throughout the profile. At CSSRI, microplots measuring 6 x 3 x 0.8 m are maintained under conditions similar to those in the field and can accommodate large numbers of genotypes. Without this type of controlled approach, the coefficient of variation in the trials is so high that selections are made solely by chance.

Once crosses have been made, with the objectives of improved yield and tolerance to the stress, the variability can be

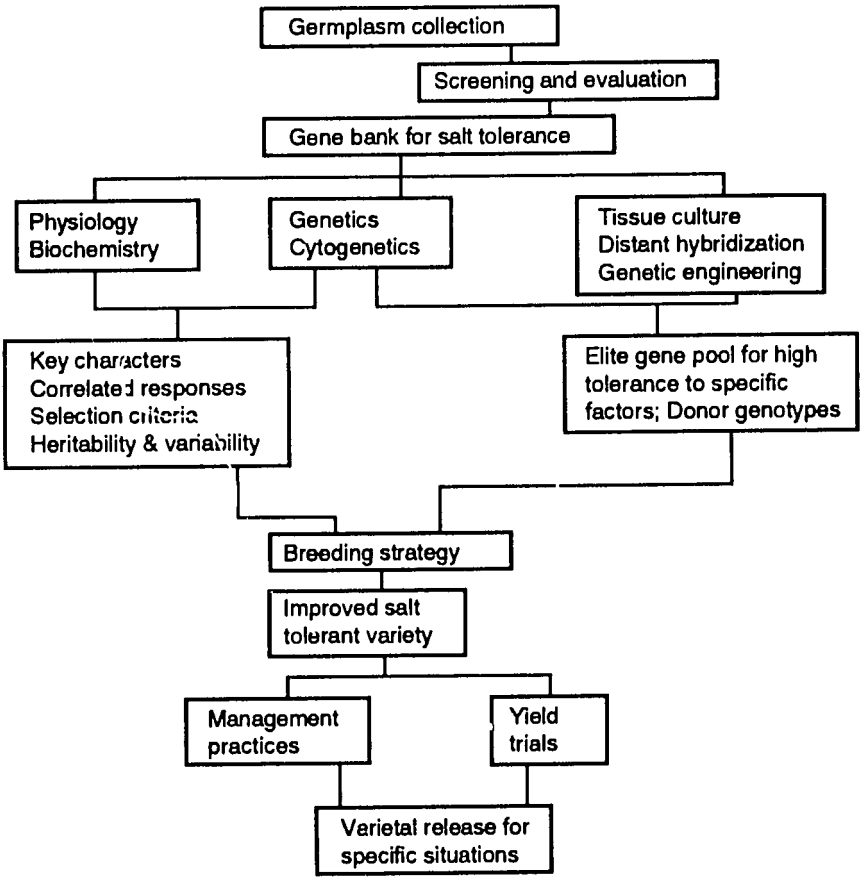

Figure 1. Integrated approach to breeding crop varieties for salt stress.

explored to determine the possibility of success in achieving an advance in the character studied. In this approach, breeding is classified into two categories, i.e. accumulation of genes favoring yield and the elimination of characters that limit expression of the variety's potential—in this case, susceptibility to salt injury. It is important, in the cases of wheat and rice for saline and alkaline areas, that progress be made in both directions simultaneously. In existing salt-tolerant types, selection criteria have not always eliminated negative genes associated with tolerance. At the same time, the plant type obtained has not necessarily provided the best combination of characters that favor yield.

Since the tolerance mechanism for germination and seedling and plant growth may not be highly related, it may be important to develop selection criteria for these different stages. The development of selection criteria should include detailed studies of the yield components. When relative yields diminish as salinity increases, it is important to know which yield components are being affected most. Factors such as sterility and tiller production may respond differently to the selection pressure of salinity. Singh and Rana (1983, 1985) and Bhattacharyya and Mishra (1986) explored such behavior of different yield components in triticale, wheat, and rice crops under salinity stress.

As already alluded to, breeders should simultaneously select for yield characters and salt tolerance. Yield potential is almost certainly governed by multiple genes—with plant type being an over-riding factor necessary for adequate expression of the other characters. In the initial stages of a breeding program, it could be assumed that salt tolerance is the product of multiple genes. For instance, tolerance at germination and at later growth stages, the effect on growth at different stages, and the effect on various yield components may all be controlled by different genes. Selection criteria against a wide spectrum of the negative or deleterious factors are most useful in selecting progenies that have the greatest general adaptation to these various stress conditions.

Varietal Tolerance vs Soil Amendments and Management

Periodic reviews of research on varietal tolerance to salt and soil mineral stresses have shown that genetic approaches have potential for solving problems of soil salinity and alkalinity (see reviews by Wright 1976, Hollaender et al. 1979, Rains et al. 1980, Christiansen and Lewis 1982, and Downton 1984). Varieties with built in tolerance to salt, soil toxicities, and nutrient deficiencies will enable small-scale farmers to obtain reasonable, stable yields by using management inputs they can afford. The failure of tolerant and susceptible varieties of different crops planted in unamended, highly saline soils indicate that tolerance alone provides little advantage where there are severe salinity or alkalinity problems.

CSSRI researchers have found a distinct and wide range of varietal tolerances in different crops (Mishra and Gill 1978; Singh 1979a,b,c; Singh and Rana 1983, 1989; Mishra 1983; Bhattacharyya and Mishra 1986; Sharma 1986; Gupta and Sharma 1990). Since soils over large areas produce only mild stresses at the onset of a salinity problem or in the first years of a reclamation project, the use of varietal tolerance is amply justified for stabilizing yields. CSRRI studies also have demonstrated that, while sensitive genotypes suffer serious yield losses even under mild stress, tolerant genotypes continue to yield well until the stress becomes severe (Joshi 1976, Sharma 1987).

Ideally, varietal tolerance should complement—not replace—soil amendments. But in practice, there are situations where amendment-based reclamation is neither possible nor economically feasible, especially if available water for leaching is of poor quality and drainage is inadequate. Under such circumstances, salt-tolerant varieties can be used during soil reclamation. A major advantage of such varieties is they put no additional financial burdens on farmers. There is also the view that the genetic approach is more relevant to developing countries, which often face severe constraints regarding availability of input resources.

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Resumen

La habilitación de suelos afectados por la sal hasta el punto en que puedan ser productivos los cultivos sensibles requiere tiempo e inversiones considerables. Una alternativa menos costosa a largo plazo es generar cultivos tolerantes que sean productivos en suelos salinos o los parcialmente habilitados. El mejoramiento para obtener tolerancia a la salinidad no es a largo plazo un sustituto del manejo del agua, pero podría contribuir a mejorar los rendimientos en las zonas costeras y en aquéllas donde se ha producido salinidad como resultado del diseño o el manejo deficientes del sistema de irrigación. En vista de las definidas diferencias observadas entre las variedades en cuanto a la tolerancia a las condiciones de salinidad o alcalinidad del suelo, se ha llegado a la conclusión de que puede ser promisorio generar variedades aptas para suelos salinos en el caso del trigo hexaploide y el arroz. No obstante, es urgente formular criterios de selección sencillos, eficientes y no destructivos para este propósito. También se señala que se deben efectuar actividades planificadas y más vigorosas de recolección sistemática y evaluación crítica de variedades de distintos cultivos autóctonas de zonas salinas, con el fin de proporcionar una amplia gama de variabilidad genética tanto para las investigaciones básicas como para los programas de mejoramiento.

Simulating Growth, Development, and Yield of Wheat in Warmer Areas

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Abstract

A validated crop growth simulation model, WTGROWS, was used to determine potential and rainfed wheat yields in different parts of the warmer areas that contrasted in thermal and humidity regimes. Historical weather data of 288 locations in Asia, Africa, and South America were used. Detailed analyses were performed for representative locations of dry and humid climates of warm, hot, and very hot thermal regimes. The results indicated that the mean yield potential of irrigated wheat was 8.80, 5.66, and 3.15 t/ha, respectively. At dry locations, yield of irrigated wheat was higher than humid ones. Yield decreased after the optimal date as a function of thermal regime, i.e., the lower the temperature the higher the reduction in yield. In late sown crops—a common occurrence—the difference between irrigated and rainfed yields became smaller. Late maturing crops are expected to yield more in very hot regions, both in irrigated and rainfed conditions, provided such varieties have reasonable grain number. Sowing in hot and very hot regions was relatively less sensitive to sowing date. Rainfed wheat yields are generally lower, but in humid environments they can be similar to irrigated yields if the crop is raised on soils that are deep, well drained, and free of root restricting layers. Early flowering in hot and very hot regions restricts root extension growth. The model can be used for determining agronomic prospects of growing wheat in more specific locations having similar environments to those used in this study.

Introduction

There is a growing interest in cultivating wheat in the nontraditional, warm areas of the tropics (CIMMYT 1985, Klatt 1988). Recent literature reports that high temperature may not be a stress (Rawson 1990) and the achievement of high yields in a few hot tropical locations (Fischer and Byerlee 1991). This suggests that crop performance and yield potential in different regions of the tropics are poorly understood. National breeding programs of several countries, as well as CIMMYT, have initiated varietal improvement programs to develop varieties more adapted to these environments. Agronomic research to identify yield constraints is also being conducted at a few places. However, the results of such location-specific experiments are often difficult to extrapolate to other regions where no or limited experimentation has been done. Experimentation at all places is desirable, but this is a lengthy and costly process.

Recently developed dynamic crop growth simulation models can evaluate the effect of climatic, edaphic, hydrologic, and agronomic factors on crop yield, production, and stability (Loomis et al. 1979, Whisler et al. 1986). Their application reduces the requirement for costly and lengthy experimentation (Loomis et al. 1979). These models are increasingly being used in climatic analysis, in agrotechnology transfer and even in directing research (Whisler et al. 1986, Jones and O'Toole 1987). Aggarwal and Penning de Vries (1989) used such a mechanistic model to establish the potential (irrigated) and rainfed yields of wheat following rice in Southeast Asia. In

this paper, a similar crop growth simulation model has been used with an objective to address the following questions for irrigated and rainfed crops:

- What are the potential wheat yields in tropical environments?
- Given the yearly climatic variation, what will be the risk associated with growing wheat?
- What is the optimal sowing date and how much reduction is expected if sowing is delayed?
- If crop duration of a variety is changed, how might yield be affected?
- How much would be the yield reduction if soil depth is restricted?

The Model: Simulation of Potential Yield

WTGROWS (*Wheat Growth Simulator*) described by Aggarwal (1991) is the model used. It is based on MACROS (Penning de Vries et al. 1989) and is written in CSMP. The model is largely explanatory and is run on an IBM PC/AT compatible computer. It simulates daily dry matter production as a function of radiation intensity and maximum and minimum temperatures for conditions where biotic and abiotic stresses do not limit crop growth. The model consists of eight sections: crop development, photosynthesis, respiration, carbohydrate partitioning, photosynthetic area, senescence, grain formation, and grain growth. The different components of the model take into consideration the climatic variation in tropical environments, particularly, the range of temperatures. A brief description of the different sections is presented in the following. Aggarwal (1991) provides more detail.

Crop development

The physiological development of wheat is divided into three developmental phases—up to seedling emergence and before and after anthesis. In WTGROWS, the number of days from sowing to seedling emergence was linearly related to temperature. The rate of pre-anthesis development was linearly related to mean temperature and photoperiod. This relationship was determined using data from 46 crops of the widely adaptable wheat variety Kalyansona grown across diverse environmental conditions. In this data set, durations of the pre-anthesis phase ranged between 39 and 114 days, and mean temperature varied between 12.5 and 24.5°C.

The rate of post-anthesis development was predicted by the ratio between actual daily mean temperature and the temperature sum required from anthesis to physiological maturity. The temperature sum (heat units) for this phase was taken as 396°C above a base temperature of 7.5°C (Saini and Dadwal 1986). Varietal differences in this aspect are generally small and negligible.

Crop photosynthesis

It was calculated by an algorithm, which is a function of the potential rate of CO_2 assimilation of an individual leaf, its initial light use efficiency, the photosynthetic area of the canopy, and daily solar radiation as proposed by de Wit (1965) and modified by Goudriaan (1986). The rate of CO_2 assimilation was insensitive to mean day time air temperatures between 10 and 30°C, but later it decreased slowly as temperature increased (Aggarwal and Penning de Vries 1989). If the reserve level in the plant increased beyond 30% of leaf and stem weight, gross photosynthesis was reduced (van Keulen and Seligman 1987).

Respiration

Respiration consisted of growth and maintenance components and were

predicted according to Penning de Vries et al. (1989) and Penning de Vries and van Laar (1982), respectively. The rate of maintenance respiration doubled for every 10°C rise in temperature.

Carbohydrate partitioning
The net carbohydrates available were partitioned into leaves, stems, roots, and grains as a function of the development stage. The relative allocation among different plant parts was based on the analysis of van Keulen and Seligman (1987). The model assumes no direct effect of temperature on partitioning; indirect effects are mediated through phenology.

Photosynthetic area
Total green area consists of leaf lamina, stems, and spikes and was determined according to Aggarwal and Penning de Vries (1989). Leaf area changed proportionately with leaf growth rate; its value was obtained by dividing the increment in leaf weight by the specific leaf weight. The latter was 500 kg/ha up to 20°C and 400 kg/ha beyond that. Green stem and spike areas were predicted according to van Keulen and Seligman (1987).

Senescence
Shading in dense crop stands accelerated the rate of leaf loss; in the model it was calculated according to van Keulen and Seligman (1987). The post-anthesis mobilization of substrates from the leaves and increasing temperature further accelerated senescence.

Grain number and growth
Source-sink balance was considered in determining grain yield. The number of grains was predicted by the ratio of mean daily temperature and radiation (the photothermal quotient) during the period from terminal spikelet formation to anthesis following Fischer (1985a). The relationship was corrected for unintercepted radiation. Grain growth was modeled by making all the net assimilates produced after anthesis available for grain growth, together with reserves equivalent to 30% of stem weight at anthesis. Grains were assumed to have an upper size limit of 47 mg as determined for semidwarf wheats by Fischer and HilleRisLambers (1978). The grains grew at a rate determined by temperature, so long as assimilates were available. Thus kernel number, grain growth rate, and potential kernel weight set an upper sink limitation to yield.

The Model: Simulation of Rainfed Yields

In this model, it was assumed that nutrients and biotic stresses were not limiting to crop growth. The program simulated crop growth and development as described in the previous section. Evapotranspiration and soil water balance were predicted using the modules L2C and L2SU of MACROS (Penning de Vries et al. 1989). Potential transpiration was calculated per day, based on Penman's (1948) approach. The actual crop water uptake was a function of the potential transpiration, the rooting depth, a water stress sensitivity factor, and the available soil water. The ratio of actual crop water uptake and potential transpiration determined the degree of water stress that influenced photosynthesis, carbohydrate partitioning and crop development as described by Aggarwal and Penning de Vries (1989). CO_2 assimilation decreased in proportion to transpiration. Up to moderate stress, carbohydrate partitioning was not effected; higher stress increased the root:shoot ratio. Within the shoots, fewer carbohydrates are allocated to leaves in stressed environments. Pre- and post-anthesis crop development was accelerated depending upon the magnitude of water stress. Effect of water stress on grain number was mediated through the effect on leaf area and the consequent reduction in light interception.

Similarly, grain growth was affected through direct effects on grain growth duration and carbohydrate availability.

The model assumed that the soils were freely drained and there was no capillary rise. Excess water above field capacity was drained to the lower soil layers or out of the simulated soil profile. The soil profile was divided into six horizontal layers. For a 1.5-m deep soil, the thickness of each of these six layers was 0.15, 0.15, 0.3, 0.3, 0.3, and 0.3 m. The soil water contents at saturation, field capacity, wilting point, and air dry level were program inputs. It was assumed that the soil profile was at field capacity at the beginning of simulation and that a good crop stand was established. The rate of root extension has been reported to vary from 12 to 34 mm per day (Gregory 1989). In the present study, roots were assumed to grow at a rate of 20 mm/day until the maximum rooting depth of 1.8 m was achieved. Irrespective of the rooting depth achieved, root growth was terminated at flowering. Soil depth was also an input. Bare soil evaporation continued until seedling emergence.

Model Limitations

The accurate simulation of photosynthetic area is important particularly at values below 3 m^2 (leaf)/m^2 (ground). Although the model provided reasonably realistic simulation of changes in leaf area index (see Aggarwal 1991 for details), there is room for improvement in the simulation of leaf growth and senescence.

Grain number in the model is determined depending upon photothermal quotient and intercepted light during the grain formation stage. Although this provides reasonable prediction, better results could probably be obtained by considering grain number as a function of spike dry matter at anthesis (Fischer 1982). Better data are needed on carbohydrate allocation to spikes during the grain formation stage.

The model does not simulate the effects of frost or other catastrophic conditions.

Heavy rainfall during the crop season can cause waterlogging and affect crop growth. These effects were not considered. The simulated rainfed wheat yields may be higher than projected in this paper when the ground water contribution to crop water uptake—not an uncommon situation in the warmer areas—is also considered in the model.

Root extension growth has been assumed to be 20 mm/day until the maximum rooting depth is achieved. However, root growth rate, as well as maximum rooting depth, may vary depending upon soil physical, chemical, and biological properties.

Weather

Fischer (1985b) classified tropical regions into very hot, hot, and warm by using mean January temperatures. Average leaf-to-air vapor pressure deficit was used as an additional variable for differentiating between humid and dry climates. Since humidity data for many locations were not available, this study uses growing season (Nov.-Feb. in the Northern Hemisphere and May-Aug. in the Southern Hemisphere) and annual rainfall for characterizing humidity regimes. Annual rainfall exceeding 1000 mm and seasonal rainfall greater than 100 mm were considered as humid; others were placed in the dry category.

For simulating potential yields, the model requires daily inputs of maximum and minimum temperatures and solar radiation. Rainfall, wind speed, and vapor pressure are also required for simulating rainfed yields. The monthly weather data sets for 288 locations—spread evenly between 26°N and 26°S of equator and between 101°W and 109°E of Greenwich in Asia, Africa, and Latin America—were collected from the Agro-climatic Data

Bank of the International Rice Research Institute (IRRI), the Philippines. The original data source of much of the data is the International Center for Tropical Agriculture (CIAT) and the World Meteorological Organization. The elevation of these locations varied from sea level to 2840 masl. The data sets included monthly means of solar radiation, maximum and minimum temperatures, and rainfall. Wind speed and vapor pressure were also available for some locations. These locations represent environments that are very hot and humid (60 locations), very hot and dry (58), hot and humid (20), hot and dry (87), warm and humid (18), and warm and dry (45).

To establish the trends in potential grain yield, crop growth, development, and yield were simulated for a nonconstraint environment for each of these 288 locations. The monthly mean solar radiation and maximum and minimum temperatures were used as the driving variables in the model. The daily values were estimated by linear interpolation.

Appropriate locations representing each of the six environmental groups were selected for detailed analysis (Table 1). Limited availability of daily weather data for several years, however, restricted the choice to a few stations. Los Baños in the Philippines—with abundant annual and seasonal rainfalls and a 24.9°C mean January temperature—was identified as very hot and humid. Coimbatore, India—with much less annual rainfall, but similar mean temperature (24.4°C)—represented a very hot and dry environment although growing season rainfall is more than 100 mm. Weather data for any true hot and humid locations could not be obtained. Sanpatong, near Chiang Mai in Thailand, was used to represent the hot and humid regions although growing season rainfall is only 72 mm—annual rainfall is 1262 mm and mean January temperature 21.8°C. Hyderabad in India—787 mm annual, 51 mm seasonal rainfall, and a 21.7°C mean January temperature—was a suitable choice for the hot and dry regions. Capitan Miranda, Paraguay—15.4°C mean January temperature and 1500-mm and 512-mm annual and seasonal rainfalls— represented the warm and humid environment. New Delhi, India—14.2°C mean January temperature and 692 and 53 mm annual and seasonal rainfalls—was selected to represent the warm and dry regions.

Solar radiation was always more in dry regions than in humid regions irrespective of the thermal regime. Relatively very hot regions had more radiation as compared to hot and warm regions (Table 1).

For determining year-to-year variability in grain yields, historic daily weather data for several years are needed. For Los Baños and New Delhi, daily weather data for 20 years were available, but for Hyderabad, Sanpatong, and Coimbatore, this data set was only for periods of 7, 4, and 3 years, respectively. For these locations, additional weather data for 13, 16, and 7 years, respectively, was generated following Supit (1986). For Capitan Miranda, only daily rainfall values for 4 years and long-term monthly climatic data were available. Since more details were not available for any other warm and humid location, Capitan Miranda was used as a representative one. Solar radiation and maximum and minimum temperatures for Capitan Miranda were assumed to be constant every year.

Results and Discussion

Model evaluation

The model has been evaluated for representative conditions of tropical environments (Aggarwal 1991). Forty-two irrigated and well fertilized wheat crops grown at Los Baños (14°N) and New Delhi (28°N) in Asia were used to evaluate the

Table 1. Environmental characteristics of selected locations contrasting in thermal and/or humidity regimes.

Thermal regime	Humidity regime	Country	Location	Latitude	Longitude	Elevation (masl)	Mean daily January weather				Rainfall (mm)	
							Maximum temp. (°C)	Minimum temp. (°C)	Mean temp. (°C)	Solar radiation (MJ/m²/day)	Nov.-Feb.	Annual
Very hot	Humid	Philippines	Los Baños	14.1°N	121.15°E	21	29.0	20.8	24.9	19.4	461	1987
Very hot	Dry	India	Coimbatore	11.0°N	78.58°E	409	29.6	19.1	24.4	24.0	176	612
Hot	Humid	Thailand	Sanpatong	18.4°N	98.59°E	314	29.7	13.9	21.8	16.2	72	1262
Hot	Dry	India	Hyderabad	17.3°N	78.28°E	545	28.4	15.0	21.7	17.8	51	787
Warm	Humid	Paraguay	C. Miranda	27.2°S	55.49°W	200	21.0	9.7	15.4	10.9	512	1772
Warm	Dry	India	New Delhi	28.3°N	77.12°E	216	21.2	7.2	14.2	17.2	53	692

performance of the model. These crops were sown on different dates over a period of several years and the mean growing season temperature experienced by these crops adequately represented the diversity of warmer regions. Simulated yields were quite close to the observed yields. Mean grain yield ± SD of observed experiments was 4361 ± 1895 kg/ha and that of simulated 4696 ± 2111 kg/ha. The actual seasonal changes in leaf area index and dry matter production were also compared with the simulated results (Aggarwal 1991). These simulations were considered accurate enough to provide confidence in the model for its use in predicting potential grain yields of wheat in similar agro-climates.

An evaluation of the crop water balance model was also performed for six experiments conducted at New Delhi (A.K. Singh, unpublished data) and four experiments at Los Baños (Aggarwal et al. 1987). Evapotranspiration and grain yield were measured at New Delhi, but at Los Baños only grain yield was recorded. Simulated evapotranspiration values were ±10% of the measured values. The simulated grain yields were also quite similar to measured yields except in three experiments where simulated yields were different from observed yield by about 30% (Aggarwal and Singh, unpublished data). Inadequate characterization of the experimental sites probably resulted in this discrepancy. The basic principles of the soil water balance have also been tested extensively in several countries (van Keulen and Seligman 1987).

Grain yields of irrigated crops

Effects of latitude and elevation—The growth of wheat was simulated for several sowing dates at 288 locations in warmer areas using long-term mean weather data. The maximum grain yield obtained at a location irrespective of the sowing date was considered as its potential yield. The simulated potential grain yields varied between 2 and 13.2 t/ha depending upon the location. For an easy understanding of the results, the grain yields (GY, kg/ha), as determined by these detailed dynamic simulations, were put into a regression relating them to latitude (LAT, degrees), longitude, and elevation (ELV, m). Due to large differences in grain yields associated with latitude and elevation, longitudinal differences, which were small, became insignificant. The regression was:

$$GY = 2270 - 40\ LAT + 5.73\ LAT^2 + 0.0763\ LAT^3 + 2.84\ ELV$$
$$(R^2 = 0.84^{**},\ n = 288)$$

From this equation, isoquant (equal yield) plots were constructed as a function of latitude and elevation (Figure 1). The grain yields exceeded 2.3 t/ha irrespective of the location. At sea level, grain yield varied from 2.3 to 3.0 t/ha between 7°S and 14°N; it increased to 5 t/ha at 21°S and 21°N. At 28°N, yield was 7.0 t/ha, but at 28°S it was only 6.0 t/ha. This decrease in yield at corresponding latitudes in the Southern Hemisphere was due to less radiation available at these sites. The grain yield potential increased with elevation at all latitudes. At 500 masl, the calculated grain yield potential was 3.5 to 4.0 t/ha from 5°S to 10°N latitude and 4 to 5 t/ha from 5°S to 12°S as well as between 10°N to 17°N. The potential varied between 5 and 6 t/ha from 12°S to 19°S and 17°N to 21°N. At the same elevation, yields were 7 t/ha at 24-25° latitude in both hemispheres. At 1000 masl, the grain yield was between 5 and 6 t/ha for latitudes below 9°S and 14°N, it increased to 7 t/ha at 16°S and 18°N. At still higher elevations, yields were calculated to increase up to 10 t/ha depending upon latitude.

In practice one may, however, find a few locations where yield potential is higher than that suggested by the above analysis. Such examples may be true because the emphasis in the present analysis was to

establish trends of potential yield across the locations and not yield potential of an individual location.

Effect of temperature—In order to determine the magnitude of change in grain yields with temperature, the above simulated grain yields were related to mean January temperatures. The month of January was selected since, at this Conference (Fischer and Byerlee 1991), tropical climates are classified based on mean January temperatures. Maximum January temperature at these locations varied between 15.7 and 36.6°C, minimum January temperature between 1.1 and 25.1°C, and mean January temperature between 8.7 and 27.7°C. The diurnal variation ranged from 3.2 to 25°C. The results showed a strong linear decline in grain yield as the mean temperature increased. For every °C increase in mean temperature, grain yields decreased by 504 kg/ha (GY kg/ha = 15741 - 504 Tmean; R^2 = 0.88) (Figure 2). Thus, in very hot (22.5-27.5°C), hot (17.5-22.5°C), and warm (2.5-17.5°C) areas, maximum yield potential is between 1.9 and 4.4 t/ha (mean 3.15 t/ha), between 4.5 and 6.9 t/ha (mean 5.66 t/ha), and between 7.0 and 9.4 t/ha (mean 8.8 t/ha), respectively.

It can also be noted from Figure 2 that, for a given temperature, the difference in yield among locations could be as much as 2 t/ha in hot and very hot regions and 6 t/ha in warm environments. This large difference is possibly due to greater solar radiation experienced by the wheat crops of drier regions.

Diurnal variation in January temperatures also affected grain yields. For the same mean temperature, there

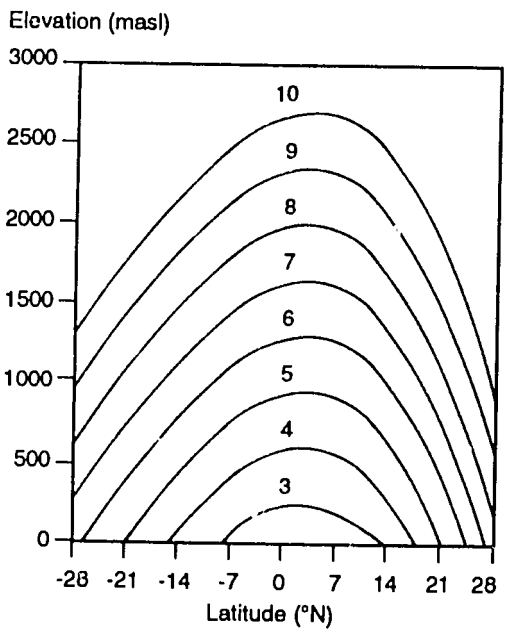

Figure 1. Isoquant (equal yield) lines of simulated potential grain yields in the low latitudes expressed as a function of latitude and elevation. Longitude effects were small and are ignored. Numbers on the lines are grain yields in t/ha.

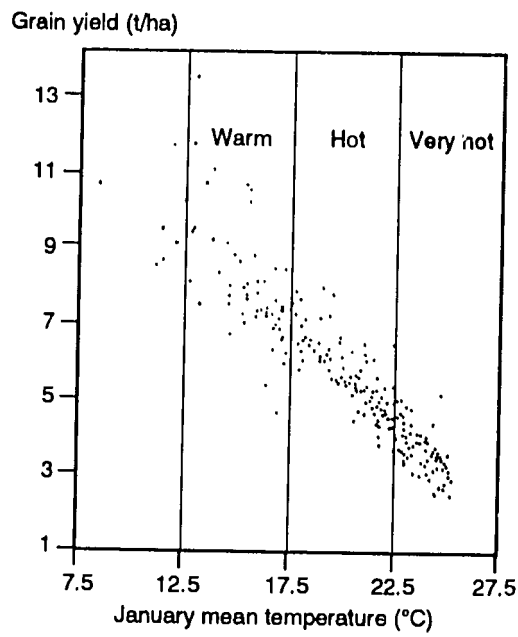

Figure 2. Relationship of grain yield with mean January temperature. Vertical lines separate very hot, hot, and warm thermal regimes.

was a small but significant reduction in grain yield as the diurnal temperature increased (GY = 16371 - 516* Tmean - 31.4* diurnal variation; R^2 = 0.89). For every °C increase in diurnal variation, yields decreased by 31 kg/ha. Thus, for a location having 20°C diurnal variation and 20°C mean temperature, yield was estimated to be 0.3 t/ha lower than the yield at the same mean temperature, but with 5°C diurnal variation. Greater diurnal variation was associated with high day time temperature, which reduced photosynthesis.

Effect of date of sowing—Sowing of wheat is often delayed due to late harvest of the previous crop or a long turnaround time. Therefore, the effect of sowing date on wheat growth and yield is very important. This was simulated using long-term mean weather data for the six representative locations described in Table 1. The simulations were made for crops sown at 15-day intervals starting 15 October (15 April at Capitan Miranda) and until 30 January (30 July at Capitan Miranda).

In the very hot and dry location, Coimbatore, the maximum grain yield of 3.7 t/ha was obtained when sowing was done late in October to 15 November; subsequently, the grain yield decreased by 24 kg/ha per day (Figure 3). In Los Baños, a very hot and humid location, optimal sowing time was between 15 November and 1 January. At these times, grain yield was 3.0 t/ha; subsequently, it declined by 24 kg/ha per day. In a hot and dry location, Hyderabad, maximum grain yield of 5.6 t/ha was obtained in sowings done between 15 October and 15 November; later, the yield decreased by 42 kg/ha per day. By comparison in hot and humid Sanpatong, optimum sowing time was between 1 and 15 November. Sowings during this period yielded 4.3 t/ha; later sowings resulted in a yield loss

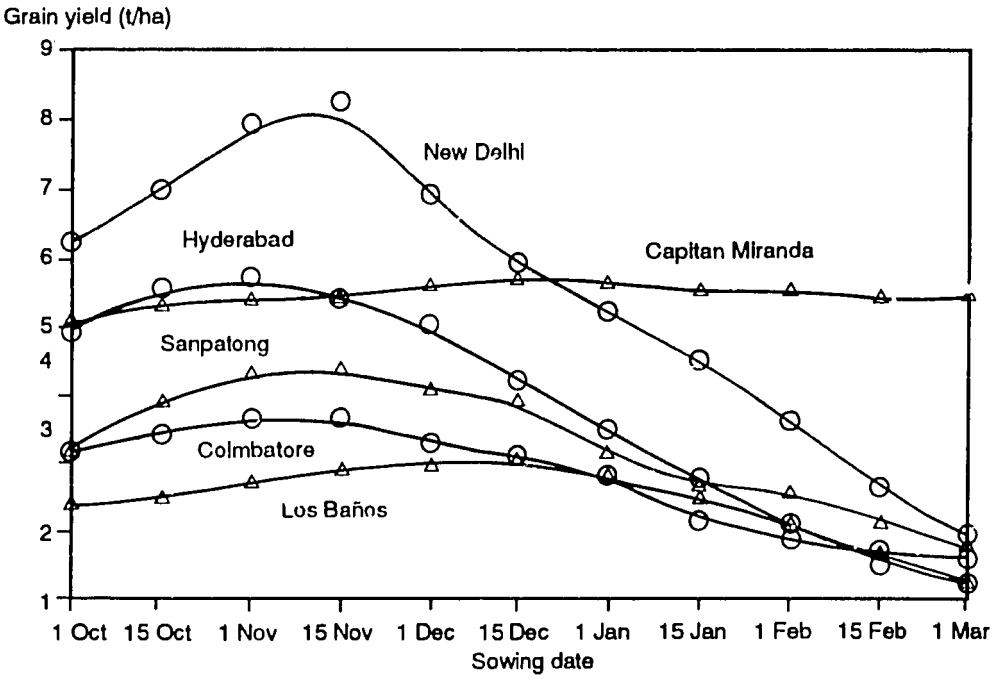

Figure 3. Effect of date of sowing on simulated potential grain yields in locations representing thermal and humidity regimes as described in Table 1. For Capitan Miranda in the Southern Hemisphere, read sowing dates plus 6 months.

of 27 kg/ha per day. The optimal sowing time was 15 November for New Delhi, a warm and dry location. The maximum yield obtained was 8.1 t/ha; later sowings decreased yield by 60 kg/ha per day. Such a sharp decrease in grain yield in similar environments is also known from field experiments (Bhardwaj et al. 1975, Hobbs 1985). The response of wheat grain yields to sowing date at Capitan Miranda was most interesting. Here, the maximum yield was obtained from 1 June to 1 September sowings. Although yield potential was lower (5.6 t/ha) due to less radiation, there was no decline in yield with late sowing. This was due to small changes in temperature over time.

Effect of increased crop duration—Crop development gets accelerated as temperature rises; consequently, crop duration is reduced. Reduced crop duration is one of the main causes of low yield in hot areas. For determining the effect of increased crop duration, pre-anthesis development rate was reduced by 30, 20, and 10% to simulate growth and development of late varieties. A 10% change is approximately equal to 5 to 7 days of increase in flowering duration. The results showed that in very hot locations, Los Baños and Coimbatore, a decrease in development rate, i.e. increased duration to flowering, resulted in a linear increase in grain yield depending upon the magnitude of change (Figure 4). A 30% decrease in development rate increased, on average, flowering duration from 49 days to 67 days and grain yield from 2.7 to 3.5 t/ha. This was due to greater light interception and hence dry matter production, which resulted in increased number of grains. However, Midmore et al. (1984) observed in the field that late genotypes produced greater dry matter but less grain yield. Grain number per unit area in these genotypes was less. Increase in grain yield in late genotypes, as calculated in this paper, assumes that the relationship proposed by Fischer (1985a) that relates grain number to the photothermal quotient is universally valid.

At Sanpatong and Hyderabad, although there was a very small increase in grain yield as development rate decreased by 10%, further reduction had no effect. At Capitan Miranda there was no effect but in New Delhi, where the climate is highly seasonal, increased duration decreased yields.

The crop duration in very hot and hot areas was between 70 and 100 days. These durations are comparable with (or often shorter than) those of other competing crops, indicating that wheat can fit very well into intensive cropping systems.

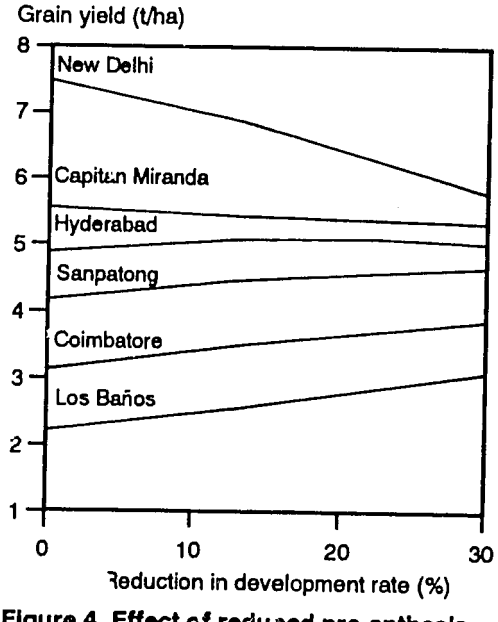

Figure 4. Effect of reduced pre-anthesis development rate on grain yield. A 10% reduction increases, on average, the flowering duration by 5-7 days. Data are the mean of 20 years of simulated yields for Los Baños, Sanpatong, Hyderabad, and New Delhi and 10 years for Coimbatore. Results for Capitan Miranda are based on long-term mean weather data.

Stability of grain yields—An important aspect in evaluating the suitability of a crop is the stability of performance over the years. Wherever historic weather data for several years are available, year-to-year variation in grain yields can be simulated. Frequency distribution analysis of this data set provides the probability of obtaining a given grain yield as well as the stability in productivity of a variety. In such an analysis, yield stability has been earlier defined as the difference between yield levels that have a probability of 75 and 25% of being exceeded in any year; the smaller the difference the larger the stability (Aggarwal and Penning de Vries 1989). Since in this study, locations vary significantly in potential yields, stability is redefined in the following equation:

$$\frac{\text{Yield at 75\% prob. - Yield at 25\% prob.}}{\text{Yield at 50\% probability}}$$

To determine year-to-year variation in grain yield, the growth of wheat was simulated over 20 years for New Delhi, Hyderabad, Sanpatong, and Los Baños and over 10 years for Coimbatore. The yearly variation in yield at Capitan Miranda was not simulated due to a lack of weather data. Actual and generated daily weather data were employed. For example, the year-to-year variation at two locations—New Delhi and Los Baños—are presented in Figure 5. The potential yield in New Delhi fluctuated between 6.5 and 8.2 t/ha depending upon the year. In six (1971, 1976, 1977, 1979, 1982, and 1988) of the 20 years, simulated grain yield was about 8 t/ha. In 10 years, the yield potential was between 7 and 8 t/ha and in 4 years between 6 and 7 t/ha. In Los Baños, grain yield varied between 2.0 and 2.8 t/ha except in 1963, when the yield potential was 3.5 t/ha.

Frequency distribution analysis indicated that in 50% of the years, grain yield exceeded 7.3, 5.0, 4.4, 3.2, and 2.6 t/ha at New Delhi, Hyderabad, Sanpatong, Coimbatore, and Los Baños, respectively (Figure 6). For these locations, the differences in grain yields between 75 and

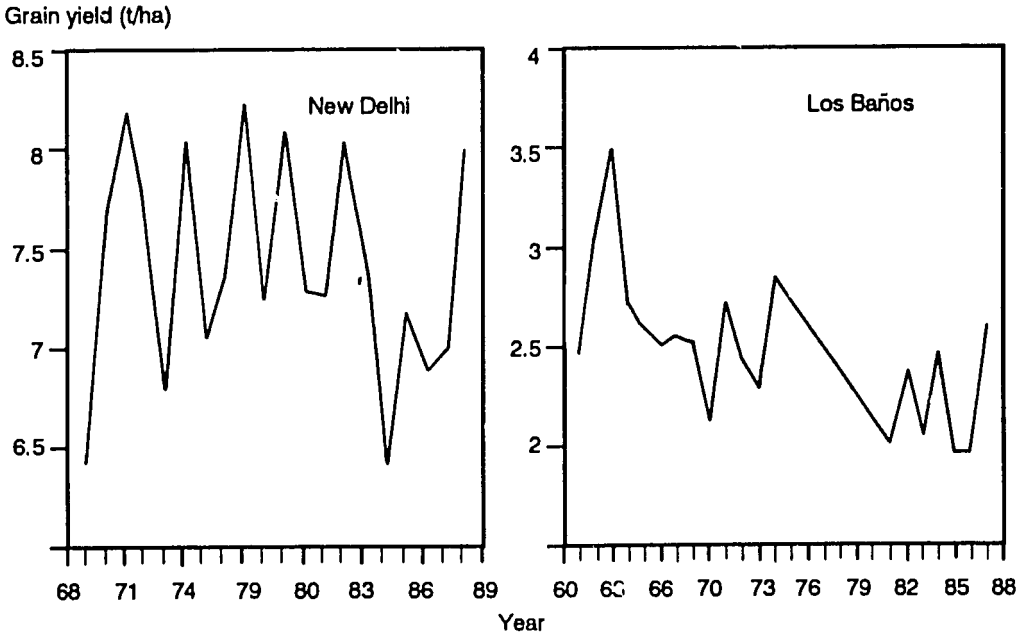

Figure 5. Year-to-year variation in simulated potential grain yields of wheat sown at optimal time in Los Baños and New Delhi.

25% probability levels were 0.95, 0.74, 0.61, 0.44, and 0.43 t/ha, respectively. The differences expressed as a proportion of yield at 50% probability level (the index of stability) were only between 13 and 17%, indicating considerable stability of wheat grain yields in irrigated and well managed conditions in the warmer regions.

Grain yield of rainfed wheat

Crop growth and yield are reduced depending upon the intensity of water stress. The water holding capacity of the soil profile and the amount and distribution of seasonal rainfall and irrigation determine the availability of water. At many places, irrigation resources are limited and the crop has to grow on residual soil moisture alone. The effect of water stress on crop growth and yield was simulated for the representative humid and dry climates of warm, hot, and very hot regions. As the soil texture and water holding capacity varies a lot in the warmer areas, it was not possible to simulate for all types of soils. In this study, for example, the comparisons were made for wheat grown on a light clay soil with 18% extractable water (Driessen 1986) that allows a maximum rooting depth of 1.5 m. It was assumed that there was no irrigation available, crop growth was entirely dependent on stored soil moisture and rainfall.

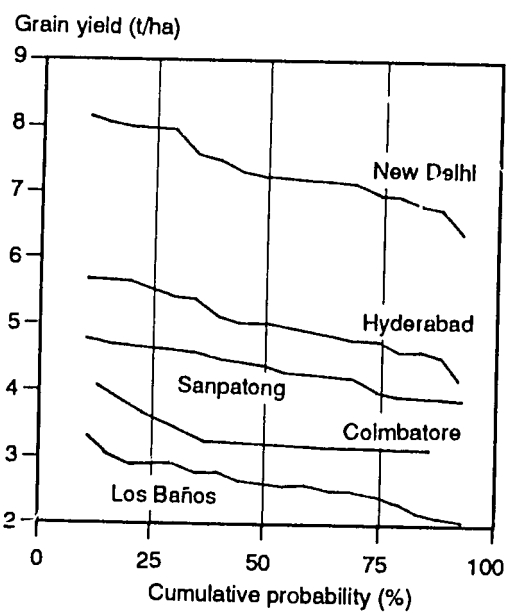

Figure 6. Cumulative probabilities of potential grain yields of wheat sown at optimal times in New Delhi, Hyderabad, Sanpatong, Coimbatore, and Los Baños. Curves are based on 10 to 20 years of simulated yields.

Effect of sowing date—The growth was simulated for crops sown at 15-day intervals starting 1 October. At all locations, runs were made for 10 to 25 years using daily weather data depending upon data availability except at Capitan Miranda where only 4 years were simulated.

At Capitan Miranda, grain yield was 5.5 t/ha, equal to potential yield, at all sowing dates between 15 April and 15 July (Figure 7). By comparison, at New Delhi, maximum grain yield of 5.7 t/ha was obtained if sowing was done in the first 2 weeks of November; later yield decreased sharply. At Sanpatong, a maximum grain yield of 3.5 t/ha was obtained when the sowing date was between 1 and 15 October; subsequently, yield decreased by 20 kg/ha per day. At Hyderabad, maximum yield of 2.3 t/ha was obtained in sowings between 1 October and 1 November; later the yield decreased by 16 kg/ha per day of sowing delay. At Coimbatore, maximum yield of 2.8 t/ha was obtained in sowings between 1 October and 1 November. A day's sowing delay after 1 November resulted in a yield loss of 16 kg/ha. In the hot and humid environment of Los Baños, sowings between 1 December and 1 January resulted in a maximum yield of 2.3 t/ha, which was close to potential yield of 2.5 t/ha.

The results indicate that, irrespective of the thermal regime, rainfed yields in humid regions were either equal or a little

less than the irrigated yields. At these places, the decrease in rainfed yields was also low in late sowings. This suggests that, if sowing is delayed in humid regions, a common situation, the yield difference between irrigated and rainfed conditions is insignificant.

Effect of increased crop duration—At New Delhi, slower crop development resulted in very sharp decreases in grain yield of rainfed wheat (Figure 8). A 30% reduction in the development rate reduced grain yield from 5.5 to 2.2 t/ha. Increased flowering duration resulted in rapid water use—leaving very little for post-anthesis use. At Sanpatong and Hyderabad, a 10% reduction in development slightly increased yields; further reduction had no effect. Very hot locations, Los Banos and Coimbatore, were characterized by significant increases in grain yield when development was slow. A 30% reduction in the development rate increased grain yield by almost 0.5 t/ha at both sites.

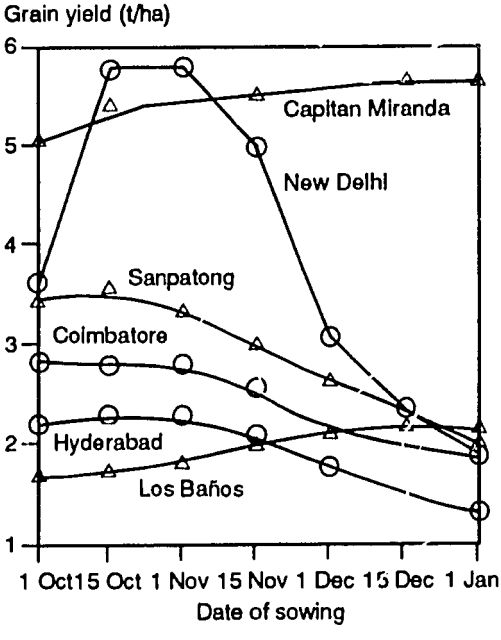

Figure 7. Effect of sowing date on rainfed wheat yields. For Capitan Miranda in the Southern Hemisphere, yields are means of 4 years of data and dates on X axis should be read as sowing dates +6 months. Data for other locations represent means of yields obtained over a period of 10-20 years.

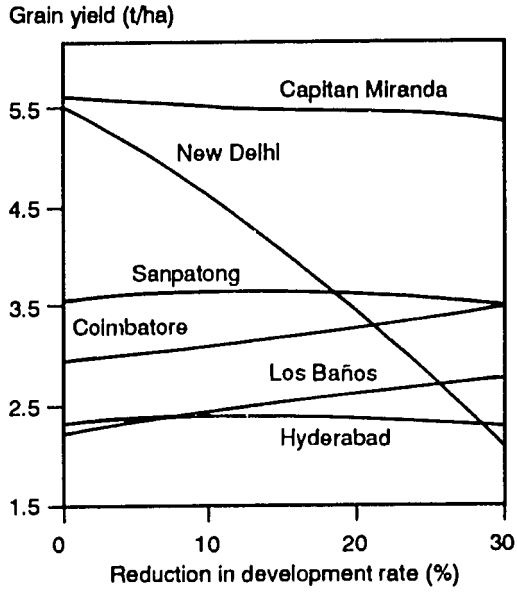

Figure 8. Effect of reduced pre-anthesis development rate on grain yield of rainfed wheat. A 10% reduction increases, on average, the flowering duration by 5-7 days. Data are means of 20 years of simulated yields for Los Baños, Sanpatong, Hyderabad, and New Delhi and 10 years for Coimbatore. Results for Capitan Miranda are based on long-term mean weather data.

Stability of rainfed yields—The year-to-year variation in rainfed yields was calculated for wheat sown on optimal dates as determined earlier. Unlike potential yields, year-to-year variation in rainfed yields was much greater. At New Delhi, Sanpatong, Hyderabad, Los Baños, and Coimbatore, there was a 50% probability of exceeding yield levels of 4.2, 3.6, 2.4, 2.5, and 2.9 t/ha, respectively (Figure 9). These yields were 42, 16, 52, 4, and 9% lower than the yields of irrigated

wheat at the same probability level. Yields at Hyderabad were the most stable (15%) followed by Los Baños (18%), Sanpatong (29%), Coimbatore (56%), and New Delhi (58%).

Effect of soil depth—Soil depth may not allow rooting depth to be 1.5 m at all places as was assumed in the earlier analysis. In many rice soils, rooting depth is restricted to 15 to 30 cm due to the presence of a plowpan. Similarly, in acid soils, liming restricts the root zone to the top 20 to 25 cm (Wall 1988). To mimic this situation, simulations were made for wheat sown on optimal dates on a light clay soil at field capacity at sowing time, but with rooting depths of either 0.25, 0.5, 1.0, or 1.5 m. The mean values of simulated yields obtained in different years are plotted in Figure 10.

At Capitan Miranda, since rainfall is high, maximum grain yield could be obtained with the 50-cm depth. Mean yield was greater than 4.0 t/ha even at a 25-cm rooting depth. At Sanpatong, Los Baños, and Coimbatore, maximum rainfed yields close to potential yield could be obtained at a 100 cm rooting depth. Even at the 50-cm rooting depth, yields were between 1.5 and 2.2 t/ha. By comparison, at Hyderabad and New Delhi, mean yields were only 2.4 and 4.0 t/ha, respectively, even when the rooting depth was 150 cm. These yields were 2.6 (48%) and 4.1 (51%) t/ha lower than the respective potential yields.

It was interesting to note that at hot and very hot locations, there was no increase in grain yield when the soil depth increased from 100 to 150 cm (Figure 10).

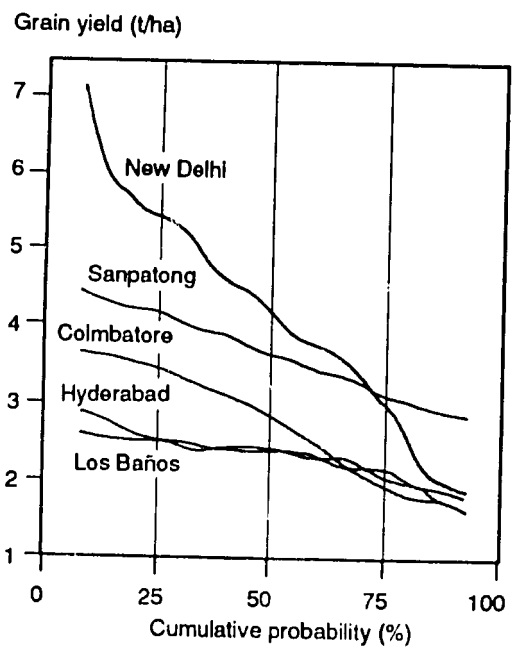

Figure 9. Cumulative grain yield probabilities for rainfed wheat sown at optimal times in New Delhi, Hyderabad, Sanpatong, Coimbatore, and Los Baños. Curves are based on 10 to 20 years of simulated yields.

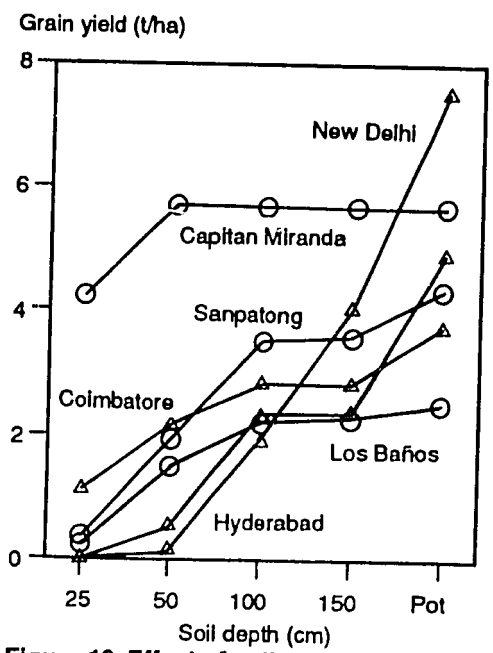

Figure 10. Effect of soil depth on grain yield of rainfed wheat sown at an optimal time. Data are means of 4 years in the case of Capitan Miranda, 10 years for Coimbatore, and 20 years for other locations.

Examination of data revealed that early flowering at these places restricted root growth to a 1-m depth and, therefore, the plants were not able to tap deeper into soil layers. In such an environment, higher seasonal rainfall in humid locations compared to dry locations supplemented water availability resulting in much higher yields. Limited data from temperate and subtropical environments indicate that root growth rate is reduced by water and temperature stresses (Penning de Vries et al. 1989). Greater research efforts on wheat roots in the warmer regions are needed. Nevertheless, the present analysis suggests that, at hot places, if the soils are deep, selection for faster root growth rates may result in higher rainfed yields.

Conclusions

The crop growth simulation shows that the average yield potential for irrigated wheat in very hot (mean January temperature, 25°C), hot (mean January temperature, 20°C), and warm (mean January temperature, 15°C) regions is 3.15, 5.6, and 8.8 t/ha, respectively. For elevations below 500 masl, yield potential in the tropical regions of the Northern and Southern Hemispheres varies between 2.3 and 6.7 t/ha. Dry regions have greater yield potential than humid ones—irrespective of the thermal regime. In general, irrigated wheat yields are stable in tropical environments, i.e., they show little year-to-year variation.

Grain yields are relatively less sensitive to sowing date in hot and very hot climates, particularly in humid environments, as compared to warm regions. Yield decreases after the optimal date at a rate dependent upon thermal regime. The lower the temperature, the greater is the yield reduction. In humid regions, this reduction is small irrespective of thermal regime. The intensive cropping systems practiced in irrigated areas often result in late planting of wheat. Under such conditions, the difference between warm and hot regions in yield potential becomes small.

The results also suggest that in very hot regions, late varieties may yield more in irrigated as well as rainfed environments provided they maintain adequate numbers of grains.

In rainfed environments, grain yield is reduced depending upon thermal and humidity regimes. For similar thermal regimes, humid regions yield more than the dry ones. The model predicts that yields of rainfed wheat are close to potential yields in humid regions, provided the soil is at least 100 cm deep, free of root restricting layers, and at field capacity at sowing time. Due to early flowering in dry and hot rainfed environments, roots are unable to penetrate deep into the soil profile. Consequent increase in stress during the post-anthesis phase results in low grain yields.

These conclusions are, however, based on a purely agronomic analysis. Pests, diseases, nutrient limitation, and waterlogging, common in warmer environments particularly in the humid regions, may restrict the full expression of yield potential.

The growth model WTGROWS, validated in low latitude (warmer) environments, is a useful tool for assessing the effect of climatic variation on wheat productivity. Due to a lack of weather, soil, and crop data for many locations, the analysis in this paper was restricted to only a few sites. The model, which is available from the author on request, can be used to determine wheat yield potential for specific locations in similar environments provided limited calibration and validation can be performed.

Acknowledgments

I gratefully acknowledge the help of Drs. F.W.T. Penning de Vries, International Rice Research Institute (IRRI), the Philippines; Herman van Keulen, CABO, Wageningen, The Netherlands; and A.K. Singh, WTC, IARI, New Delhi, in developing the model. Dr. Singh also provided the unpublished ET data. Most of the weather data was obtained from IRRI's Agroclimatic Unit. IARI provided the data for New Delhi; Drs. P. Wall and M.M. Kohli provided data for Capitan Miranda and some other locations in South America.

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Resumen

Se usó un modelo verificado de simulación del desarrollo de los cultivos, WTGROWS, para determinar los rendimientos potenciales del trigo en condiciones de secano en distintas partes de las zonas cálidas, que contrastaban en cuanto a las características térmicas y de humedad. Se emplearon datos históricos sobre el clima de 288 localidades de Asia, Africa y América del Sur. Se efectuaron análisis detallados de localidades representativas con climas secos y húmedos y temperaturas templadas, cálidas y tórridas. Los resultados indicaron que el potencial de rendimiento medio del trigo irrigado era de 8.80, 5.66 y 3.15 t/ha, respectivamente. En las localidades de clima seco, el rendimiento de trigo irrigado fue superior al obtenido en las partes húmedas. El rendimiento disminuyó después de la fecha óptima como función del régimen térmico, es decir, cuanto más baja fue la temperatura, mayor fue la reducción del rendimiento. En los cultivos sembrados tardíamente, un hecho frecuente, fue menor la diferencia entre los rendimientos del trigo irrigado y los del cultivado en condiciones de secano. Se espera que los cultivos de madurez tardía tengan un rendimiento mayor en las regiones muy calientes, tanto en condiciones de riego como de secano, siempre que esas variedades tengan un número razonable de granos. La siembra en las regiones calientes y tórridas fue relativamente menos sensible a la fecha de siembra. Los rendimientos del trigo en condiciones de secano son en general más bajos, pero pueden ser similares a los obtenidos con la irrigación si el cultivo se produce en suelos profundos, bien avenados y exentos de capas que restrinjan el desarrollo radical. La floración precoz en las regiones calientes y tórridas limita la extensión de las raíces. Se puede usar el modelo para determinar las perspectivas agronómicas del cultivo del trigo en localidades más específicas, que tengan ambientes similares a los utilizados en este estudio.

PANEL DISCUSSIONS

Are the objectives of sustainability and disease and insect control incompatible with respect to tillage and cropping systems in wheat?

Panel members: H.J. Dubin, K.K.M. Nambiar, R.L. Burton, P.R. Hobbs, E.M. Reis, R. Derpsch, and D.R. Byerlee

A working definition of sustainability was introduced as "increasing productivity at least as fast as population growth without degrading the resource base." Some would suggest that increased stability may be included while, in many instances, it may be necessary to increase the resource base.

In a sustainable system, soil resources and physical properties must be conserved. One aspect of this is adequate infiltration rates and hence erosion control. In the areas of South America discussed, ground cover is essential for increasing infiltration—it was suggested that ground cover should approach 100% for maximum benefits.

In some instances, high levels of ground cover can be effective in reducing insect populations—the greenbug was cited as an example. This aphid appears to respond more to the surroundings of the host plant than to the host plant itself and is repelled by shorter wavelength emissions; more greenbugs are trapped over bare soil than over a soil surface covered by plant residues. As an example, 250 greenbugs were reported trapped per foot of row in a conventionally tilled wheat field, while in a zero-tillage wheat plot, aphid numbers were reduced tenfold—much below the economic threshold level. It was also suggested that, by the use of modified seeding dates and resistant varieties, greenbug populations could be even further reduced.

Stem borers in the rice-wheat systems of Asia provide another example where zero tillage did not result in increased insect problems, apparently because rice straw, although not burned, still decomposed rapidly enough to prevent substantial stem borer carryover.

Thus, although at the moment it was considered that generally accepted insect control measures are probably not compatible with sustainability, opportunities exist within emerging tillage and cropping systems to control many insects in a sustainable manner.

However, while residue retention reduces some insect problems, it generally increases disease problems caused by *Bipolaris sorokiniana* (spot blotch) and *Drechslera tritici-repentis* (tan spot). Association with crop residues is one of the important survival mechanisms of these two pathogens. Residues provide substrate for their saprophytic phase and the organisms sporulate continuously until the residue substrate is depleted. After total decomposition, *D. tritici-repentis* is eliminated from the field, but *B. sorokiniana* can survive for up to 37 months (in southern Brazil) as free dormant conidia.

Hence, zero tillage increases the disease inoculum density and severity. However, it is possible to manage the diseases within the reduced tillage systems by crop rotation. To design such a system, it is important to determine the period for compete depletion (decomposition) of infected crop residues and the survival period of dormant conidia in the soil. These will determine the frequency of wheat in the cropping pattern. Nonsusceptible crops (e.g., pulses) can be grown in the intervening winter cycles.

Burning the stubble can significantly reduce disease carryover, but can increase the risk of erosion. Thus, there may be conflicts between the retention of stubble for erosion control and possible reduction of insect populations and disease levels.

It was suggested that there are a number of research and management directions. First, land management and crop rotations should not be considered to be rigid. It was stated that diseases make crop rotation compulsory. The use of resistant green manure crops was suggested, or the substitution of wheat by another winter crop for a number of cycles—the period for which wheat is absent from the rotation depending on the decomposition rate of residues. Second, genetic resistances to diseases and pests were considered essential. Third, tillage systems could be alternated and planting dates could be manipulated to reduce disease pressure.

The study and application of zero or reduced tillage were considered to be of high priority. Reduced tillage reduces the input costs—essential for profitable cropping—but can introduce new problems associated with pests and diseases. Research on zero or reduced tillage will require the mobilization of multi-disciplinary research teams working over relatively larger time frames than currently is the case.

The adoption of zero tillage has been shown to have conflicting effects on different pests and diseases. While it is far from well researched, some examples of effects include decreases in weeds (South Asia) and aphids (USA), in the latter case marked decreases. Stem borer (South Asia) does not appear to be increasing with zero tillage. On the other hand, tan spot has increased dramatically with the introduction of the system in South America, although this is not general across all foliar pathogens and is greatly affected by seasonal conditions.

The panel considered that it is becoming increasingly necessary to examine effects over the long term, not only in reduced tillage systems (which may not be appropriate for all regions or zones), but also in conventional tillage systems. The panel questioned whether this research is more efficiently carried out through long-term experiments, by crop monitoring in farmers' fields (and correlations with their practices), or by some other methodology. It was felt that any changes in agricultural management must be studied, not only in relation to soil physical and chemical factors, but also for effects on soilborne pathogens and pests and the soil micro-flora in general—two areas considered to be poorly researched.

There was consensus that cropping systems should be flexible. While zero tillage may offer benefits in the short term, disease buildup or soil compaction, etc., may make it essential for one or several cycles of tillage to be inserted to alleviate these types of problems. Resistant alternate crops may have to be grown from time to time to reduce disease inoculation. It was felt, however, that most disease problems (particularly foliar and spike diseases) would be reduced, assuming sufficient resources were allocated to resistance breeding, although this resistance might not totally obviate the necessity for an integrated disease management approach.

It was generally agreed that current research and application of modified tillage and cropping systems appear to have a strong bias toward sustainability issues. Attention (particularly in South America) is being paid to soil physical and chemical resource bases. A central aspect of research into tillage/cropping systems appears to be disease and pest control. Further research on sustainability of systems is required and will be best accomplished by multi-disciplinary research teams.

Has disease research for the warmer areas been cost-effective over the last 10 years?

Panel members: J.P. Tandon, H. Fehrmann, Y.R. Mehta, P. Mooleki, R.A. Fischer, and G. Bekele

The consensus of the discussion was that disease research in the past 10 years had been cost-effective. When considering the value of losses from disease control, particularly in relation to genetic advances, one must estimate the losses that would have occurred over time if the disease research had not been undertaken, i.e., the value of the maintenance component of this research.

Generally speaking, all economic analyses of the results of disease research have been favorable in the past. Innovative (or "imaginary") research that may appear expensive now, with the outlook of small practical gains, may become highly cost-effective in the long term.

Of course, in the warmer areas, there is considerable research spin-off from the traditional wheat areas that could be considered progress at very low cost. It is considered unlikely that we would be considering the priority diseases (spot blotch, tan spot, fusarium) or soil diseases in the warm areas today if the other foliar pathogens had not been controlled by genetic advances from the cooler environments. On the other hand, disease research in the warmer areas may have very great benefits to wheat growing in the traditional areas.

It was considered that breeding for disease resistance will always be cost-effective. However, it was recognized that, in the warmer areas, it will be long-term research because of the requirements for incorporation of other traits as well as enhanced phosphorus uptake ability, resistances to relatively new and poorly research diseases, and tolerances to high temperature and high aluminum concentrations in the soil. Genetic resistance can have enormous benefits. For example, IAPAR 6-Tapejara, released in the late 1980s and less susceptible to *B. sorokiniana*, netted the state of Paraná in Brazil US$10 million in additional revenues in 1988.

Although there was agreement that breeding for disease resistance was always cost-effective, it was pointed out that there was reticence on the part of donors to provide funding over the long time frame (at least 10 years) necessary for incorporation of disease resistance in addition to all the other characters described above.

There appear to be large gaps in knowledge of the host-pathogen relationships for the diseases more common in the warmer areas. While virulence analysis should be quite valuable, it is rarely sufficiently supported financially.

The form of disease control—whether genetic, chemical, or biological—will be dictated by economics. The particular control solution may change with time. For example, chemical control may be phased out as genetic resistance becomes available. Indeed a combination of control methods may be used and the mix of that combination will be dynamic.

The panel considered that applied research into chemical disease control has usually been cost-effective. Newer chemicals and more defined spraying schedules can be used to increase the profitability of the practice to farmers.

This has been accomplished in Paraná where research has shown that, by considering the disease "threshold" level for the first application, the spacing of sprays, and the crop stage after which fungicide application becomes uneconomic, fungicide application can be reduced by at least one spray without diminishing results.

However, there is an increasing tendency for government funding agencies to lean toward funding those projects that deal with ecological aspects of disease control. In addition, government regulations are increasingly being made to protect the environment. This has had the effect of dramatically decreasing research into the development and use of chemicals for disease and pest control. Therefore, while it may not always make the best sense, funds may be allocated to the ecologically sound control approaches—breeding for resistance is ecologically sound.

It was suggested that, in the question addressed by this panel, the term "sufficient" should be substituted for "cost-effective". There was little doubt in the minds of the panel members that research in the last 10 years has been cost-effective. However, present funding levels were considered inadequate for the work envisaged in the next 10 years. It was concluded that donors should be made more aware (by research administrators) of the current gains in productivity due to disease research, although there have not been enough solid quantitative analyses of the cost/benefit relationships of such research. Economists and pathologists need to be encouraged to do more in this area. It is particularly important that donors understand the funding requirements for this problem and the long-term nature of research related to integrated disease control.

Breeding for tolerance to the major environmental stresses in the warmer areas: Where should we be going?

Panel members: S. Rajaram, K.N. Singh, M.E. Sorrells, J. Nisi, L. Olugbemi, O.A.A. Ageeb, and E. Acevedo

The majority of the panel members and speakers emphasized the need for a more integrated team approach to breeding for tolerance to the major environmental stresses. The basic physiological processes are poorly understood for tolerance to the unique abiotic stresses of the warmer areas—drought and heat—and, indeed, even the characteristics of the stresses themselves have not been fully defined.

Obviously, the mechanisms involved in the alleviation of each of these stresses will more than likely be different. For more efficient advances in breeding for stress tolerance, breeders require that physiologists better define the traits for which they should be selecting. In addition, agronomists should be involved in these crop improvement programs as, for example, the expression of genetic potentials may be restricted or enhanced by soil compaction, soil water holding capacity, the presence of surface mulches, previous crop, seeding depth, etc.

Breeding Methodologies

It was suggested that conventional breeding strategies of evaluating material for the trait in question, crossing tolerant material, and selecting for the trait will be the most appropriate for the near future. The salt tolerance work at Karnal, India, was cited as an excellent example where a well focused program has selected material much improved in salt tolerance through the use of conventional methodologies.

However, it was considered that some newer techniques may improve the efficiency of the breeding programs. For example, by the development of random lines, related lines, or near isogenic lines differing in tolerance to the stress under study, we may better understand the genetics of the trait and identify selectable genetic markers that could then be used for evaluation of other crosses—selection for the marker directly rather than the trait.

It was further suggested that more use of wild relatives of wheat should be made in stress tolerance breeding. Landraces and well adapted old cultivars could also aid in understanding the characters required for the various abiotic stresses and could contribute to higher tolerance in genotypes with high yield potential.

Heat Tolerance

As with drought, it is essential to more clearly define which type of heat stress tolerance is required.

In India under rainfed conditions, wheat seeded at traditional optimum dates suffers from drought stress following anthesis. By earlier seeding, better utilization of stored soil moisture can be attained. In this case, seeding and early vegetative growth take place under elevated temperatures and juvenile heat tolerance is required. In other areas, heat tolerance is required during the grain-filling phase.

Physiologists in the Indian wheat program have studied the effect of heat on various growth stages. They found that the growth stage between emergence and double-ridge formation exhibits the greater variability between genotypes than the other stages studied. Several lines have been identified (e.g., Hindi 62) that reduce this vegetative period very little under high ambient temperatures.

Behavior in one environment (e.g., India above) may or may not be indicative of the reaction in another. In particular, the effect of relative humidity in relation to high temperature stress was mentioned.

Heat avoidance may also be possible through selection of deeper roots to extract more soil moisture and maintain transpiration, therefore reducing canopy temperatures.

Finally, it was suggested that more work is required on the effect of high temperature on partitioning of assimilates—it appears that, while assimilates are generally not limiting, high temperatures may affect the control of partitioning of assimilates to the detriment of the grains.

Drought Tolerance

"Drought stress" encompasses those situations where the stress is:

- Encountered in the early vegetative stage.
- Intermittent during mid-season (Mediterranean-type drought), but finally becomes a terminal stress.
- Progressively developed when wheat is grown on residual soil moisture.
- Aggravated by an unreliable supply of irrigation water.

As with heat tolerance, there are many pieces of (often contradictory) information suggesting mechanisms of drought tolerance. It was suggested that these data had never been fully applied or exploited due to a lack of integration between disciplines as to which are problems of genotype and which are problems of crop management. Again, here, resistance and/or avoidance may all be valid mechanisms with which to work—their relative contribution possibly depending on the type of drought experienced.

Root growth is probably the most important factor in certain types of drought tolerance. It was admitted that root growth is hard to quantify in many situations. However, good measures of differences in moisture extraction and hence rooting activity, between genotypes can be determined under residual soil moisture environments. However, methodologies should be further developed.

In Argentina, drought develops early in the growth cycle. Lengthening of the vegetative period appears to be connected to drought tolerance under these conditions.

Multiple Stress Conditions

Many warmer environments have multiple abiotic stresses—high temperature at seeding and during grain filling, drought and heat stress during grain filling, and very cool temperatures at anthesis followed by rapidly elevated temperatures during grain filling.

In some countries, seed production infrastructures are not developed well enough to allow a multiplicity of varieties, each one adapted to a particular stress experienced in different regions of the country. Bangladesh, a case in point, has various regions that experience drought,

heat, waterlogging, and salt stresses either in combinations or singly. The approach has been to screen segregating generations in stress" hot-spots" to develop multi-stress tolerant varieties. Progress has been made using this traditional approach, but it is felt that stress tolerance could be enhanced more quickly if suitable screening methods based on physiological parameters were available.

It was suggested that if genotypic markers are determined associated with the various stress tolerances, RFLPs may offer advantages in selection efficiency with these multiple stresses in particular.

In conclusion, the greatest immediate requirements are to:

- Collate known information on morphological and physiological traits associated with stress tolerances.
- Further study the issues that are unclear or contradictory.
- Utilize selection criteria established in physiological studies.
- Establish interdisciplinary teams of plant breeders, physiologists, and agronomists.

Which direction do we go on nutrients—fertilizer or efficiency?

Panel members: R. Graham, O.A.A. Ageeb, L.A. Leon, J. Döbereiner, A.P. Mgonja, B. Rerkasem, C.E. Mann, C. Camargo, and R. Radriantsalama

Acid Soils with High Aluminum/Manganese and Low Phosphorus Availability

It was generally agreed that, in many instances, an integrated approach to plant nutrition will be required—that is, there should be a balance between breeding for enhanced genetic tolerance to nutrient deficiency, unavailability, or toxicity, and the rational use of fertilizers and soil amendments.

For example, the cost of fully amending a soil problem, such as highly acid soils with toxic levels of aluminum (Al) and manganese (Mn), may be prohibitively high. Genotypes with enhanced tolerance to these stresses could produce acceptable yields on soils that have been partially amended at an affordable cost to farmers.

In addition, soil amendments are usually only successful in the upper soil layer. Under irrigated conditions where the wheat roots will generally be restricted to that layer, genetic tolerance to the soil toxicities may not be necessary. However, in rainfed conditions for example in Sao Paulo, Brazil, the crop becomes periodically drought stressed as the roots cannot extract moisture from the subsoil, which contains high levels of Al and, in most cases, Mn. Enhanced tolerance to toxicities of these elements would allow the crop to take advantage of the subsoil moisture and hence reduce the drought stress during periods of low rainfall.

The panel considered that, in these soils where applied phosphorus (P) is fixed, genotypes with enhanced efficiency are required. While in Brazil there is some work on improving the P utilization efficiency, it appears the greater opportunities relate to increased uptake efficiency for which genetic variability has been identified. Caution was expressed regarding selection for P efficiency. Scientific literature provides many examples where researchers, while showing massive differences between genotypes in well managed pot experiments, have not been able to obtain agreements with those results from field verification experiments. As P is involved in every single plant process, there is a plethora of interactions—P x temperature, P x maturity, etc. It was suggested that P is an element for which one might practice "yield-independent selection" in which research should define the particular mechanism involved and then selection should be made for that mechanism, not yield. The large number of interactions cannot be avoided when P efficiency is integrated through yield.

An additional difficulty (and, indeed, research opportunity) is the interaction of the genotype and vesicular-arbuscular mycorrhizal (VAM) associations. Studies have shown that the relative P efficiencies of a group of genotypes can be highly influenced by the type of VAM fungi present. The P source and its solubility can also affect these relationships.

Micronutrient Deficiencies

Whether micronutrient deficiencies should be ameliorated by breeding for efficiency or by application of the nutrient concerned is a complex issue. In India and

Australia, for example, the application of small quantities of zinc (Zn) lasts a number of years, but may not always achieve potential yield under water limiting conditions because of Zn deficiency in the subsoil. However, in some instances, even assuming a fertilizer supply and a functioning infrastructure (and that farmers can afford even these small inputs), it would seem wise for breeders to concentrate on the major selection criteria of heat and drought tolerance and disease resistance although there is evidence to suggest that these are nutrition-dependent.

On the other hand, with boron (B), the limits of soil contents, between which toxicity and deficiency are developed, are very narrow. On some soils, there is a strong possibility of overdose if B applications are made in consecutive years. This factor presents a particular problem when dealing with farmers of low literacy and is a case where breeding may be desirable.

Conversely, in Bangladesh, it appears that B application in 1 year has no residual value in following years. This simplifies the extension of the correction of B deficiency by nutrient applications.

A suggestion was made that balanced micro-element nutrition could be aided by the application of about 10t/ha of farmyard manure (FYM). While this may be possible in some areas (e.g., India), there are vast areas of the warmer areas that simply do not have the animal concentration to achieve this—for the wheat area in Brazil alone, this would require 400 million tons of FYM annually. In addition, FYM produced by animals fed deficient fodder may itself be deficient.

It seems then that it may be unwise to make a categorical decision as to when to breed for efficiency or when to apply nutrients, but that this must be decided on a case-by-case basis. In formulating a decision to breed for increased nutrient efficiency, it was suggested that the following issues should be considered:

- What is the extent of the deficiency and what is its priority in relation to the established breeding objectives (drought and heat tolerance, disease resistance, etc.) ?
- Does variability exist? Do screening techniques exist? What is the heritability of the nutrient efficiency?
- What is the economic value of genetic efficiency in relation to the reduced amount of the nutrient's application requirement in a depleted situation?

Finally, it was suggested that the incorporation of nutrient efficiency might be considered as just another component of wide adaptability.

Nitrogen

The question of genetic variability for N use efficiency was raised. It was pointed out that considerable work has been done on N efficiency in wheat. Generally, this has been defined as yield in relation to supply (and therefore includes uptake and utilization efficiency). This has increased as selection for increased grain yield has proceeded and it appears that this can increase still further unless some requirement is imposed for increased grain N content, in which case the N efficiency would decrease.

Most work shows that increased N efficiency between genotypes has been due to differences in yield potential. There are occasional instances where genotypes have been identified that have increased efficiency at low N supply (usually due to superior root proliferation), but this has been at such low yield levels as to be not considered important in relation to food

Suggestions were made for more diverse N studies. Possibilities exist for N supply to come from other components of the cropping system through leguminous species. With perennial crops in the rotation (e.g., alfalfa), there may be some redistribution of nutrients from the subsoil to the topsoil.

Further, other alternatives to N fertilizer have not been fully researched. Perhaps N efficiency can be enhanced through specific genotype x N-fixing microorganism interactions for which selection might be made.

Diagnostic Nurseries

Several participants spoke on the value of assembling genotypes that are tolerant or sensitive to specific nutritional deficiencies (or toxicities). The value of international nurseries of this type would be to identify areas of existing or potential deficiencies. Such a nursery is currently being assembled in Thailand for the identification of B deficiency. A range of wheat lines with differing sensitivities to B deficiency will be sown at selected sites in a collaborative program involving Thailand, Bangladesh, Nepal, and India. Other sensitive or indicator species (grams, sunflower, etc.) may be included in this "probe" nursery.

Networking to overcome problems in the warmer areas

Panel members: R.A. Fischer, A. Baier, H. Fehrmann, S. Rajaram, M.M. Kohli, J. Nisi, H.J. Dubin, C.E. Mann, A.B.S. Hossain, C. Diederichs, A. Razzaque, C. Riede, B. Somrith, O.A.A. Ageeb, P. Mooleki, J.P. Tandon, and J. Chavez

Introduction

R.A. Fischer

The history of CIMMYT shows the success of informal networks where a coordinator (usually CIMMYT) and an interested group of persons work together toward a specific goal. This informal situation has been very efficient with a low overhead and very effective. However, today, we have been asked to give our attention to more formal mechanisms or networks.

First, it would be useful to list the activities found in such formal networks. Obviously, a flow of information and/or germplasm between distant places is involved. Also involved is the execution by network members of common experiments agreed upon prior to the initiation of the network and—something that is often neglected—analysis of results across locations if they are to be exploited to full advantage. It is more efficient if people can travel within the network area from time to time to visit one another's experimental sites and to observe the different agricultural environments. Meetings and workshops are also a vital component of these networks.

Some institution must take the responsibility of coordinating the network and this also usually involves obtaining funds to carry on the activities outside the national programs—in other words, visits between countries and meetings in some common location. All this can add up to a substantial amount of money. It has been stated no viable network can function for under US$50,000 per year.

Existing networks

There are a number of informal networks focused on warmer area problems already underway among many of you. First, let's look at nurseries coming out of CIMMYT that can be considered networking activities.

- Warmer Areas Screening Nursery—This unreplicated screening nursery has been distributed for several years. It is summarized periodically and results distributed, but it has not been analyzed in any great detail. Clearly, germplasm distribution is the main objective.

- Acid Soils Screening Nursery—This nursery goes to selected parts of the warmer areas as well as to some temperate locations.

- Semi-Arid Wheat Screening Nursery—This nursery goes as much to temperate areas as it does to warmer areas, but there is much interest in the warmer areas.

- Scab Resistance Screening Nursery—This relatively new nursery brings together material from China and South America and distributes it to breeders working on scab resistance in more than 30 countries in South America, Europe, Asia, and Africa.

These four nurseries have evolved over the last decade at CIMMYT and are really fundamental to the activities that CIMMYT thinks it should be involved with. We also have some regional nurseries produced in collaboration with

national programs. For example, Thailand produces a Hot Climate Screening Nursery, which has been underway for the last 4 or 5 years and mostly grown in South and Southeast Asia. A few sets are also sent to parts of South America and Africa. From the group in Paraguay, there is the Advanced Lines of the Southern Cone (LACOS), prepared with the involvement of the Cooperative Research Program of the Southern Cone (PROCISUR), which is focused as much on the temperate areas of the Southern Cone as on the warmer areas.

Spot blotch—Probably one of our most formal networks currently in existence is the one devoted to spot blotch (*Helminthosporium sativum*, syn. *Bipolaris sorokiniana*). Underway for more than 2 years, it involves experts from Germany, Brazil, Israel, and CIMMYT. Supported by the German Agency for Technical Cooperation (GTZ), this network has been very effective in linking pathologists in Londrina, Brazil, with scientists in other parts of the world.

Boron—During this conference, we heard about the Boron Deficiency Network in wheat supported by the Australian Centre for International Agricultural Research (ACIAR) and involving CIMMYT and Chiang Mai University in Thailand. This network has a regional focus, Thailand in particular, but involves Bangladesh, Nepal, and parts of India as well. It is trying to elucidate the extent of B deficiency in wheat in that part of the world and to devise solutions to the problem through genetic resistance and fertilizer strategies.

Rice-wheat—A network devoted to the so-called sustainability of rice-wheat farming systems is in its embryonic stages. Its focus is exclusive to South Asia where there are 12 million hectares of these two crops grown in rotation. This is a very important cropping system with a number of soil problems, declining yields in many cases, and low productivity in some cases. This network would provide a mechanism to bring together specialists from Pakistan, India, Bangladesh, and Nepal to work in a coordinated fashion at key South Asian sites. Although I include this as an existing network, its status is somewhat uncertain because funding is still being negotiated. For CIMMYT and the International Rice Research Institute (IRRI), this network has the potential of becoming a major effort in the 1990s.

Suggested new networks

Heat tolerance mechanisms—The Sudanese, in particular Dr. Ageeb here and his colleagues, and others have been concerned that we have not significantly advanced our understanding about the genetic and physiological basis of adaptation to warmer areas, nor even about the key underlying aspects of management for high yield in these environments. When the project sponsored by the United Nations Development Programme (UNDP) for work in the warmer areas was revised, a fourth position was added and approved. This new position will be filled by a physiologist who will work specifically in collaboration with many specialists in the warmer areas on the issue of trying to better understand the mechanisms of heat tolerance. For example, are there genotypes already adapted to hot, dry or moderately dry places such as Sudan, Bolivia, or southern India? If so, what are the underlying mechanisms of their tolerance? Are they medium-cycle wheats? Do they have deep roots? Do they have biochemical or physiological tolerance? From a management standpoint, how important are water-nutrient supplies and mulching in keeping the crop cool? Since we do not have to worry about diseases in these warm, dry environments, we hopefully can devote much of our time to answering these questions.

Even with the extra position, I think we can only do a fraction of the job based in Mexico. We really need to have contact with four or five locations in the warmer areas where there are scientists interested in collaborating in this type of activity. There should be a small international experiment that involves scientists taking some common measurements, sharing the results, getting together to discuss them, and trying to resolve some of the issues regarding the principles of heat tolerance.

We have partly become involved in this work because donors are urging the International Agricultural Research Centers (IARCs) to move upstream, i.e., do more basic research. This philosophy is right in the sense that they think that after 20-25 years of IARC activities, it is time that national programs take over conventional breeding and agronomy work. Therefore, the IARCs should be doing more basic research—obviously the donors think about molecular biology, but physiology is definitely another avenue.

Soybean-wheat cropping systems—Currently, there are more than 6 million hectares of wheat planted after soybeans in Argentina, Uruguay, Brazil, Paraguay, and Bolivia. It is a system with serious sustainability problems quite different from the ones found in the rice-wheat system in South Asia. CIMMYT feels it should get involved in this work especially if the countries involved do not take up the issue as part of a regional effort, however, we are still debating how to go about this involvement.

Bacterial diseases—The importance of these diseases throughout the warmer areas is still an open question.

Aphid control—Regarding aphid control, our Sudanese colleagues have suggested networking in the areas of genetic resistance and integrated pest management. Earlier in the conference, we certainly heard what can be achieved in this area.

Drought—The drought issue has been discussed for several years between ICARDA, CIMMYT, and a possible donor agency, but not much has happened yet in terms of putting the details together.

Utilization of new breeding techniques—This involves alien species and molecular probing techniques such as restricted fragment length polymorphisms (RFLPs). CIMMYT now has a small operating laboratory capable of carrying out most relevant molecular techniques. We can test some of the ideas that have been discussed during this conference and compare them with conventional breeding methodologies. CIMMYT has found it easier to get funding for such investigation because donors are worried that many of these techniques may be locked up in private industry in developed countries. They feel it is very important that public centers such as CIMMYT keep up with the private sector's developments in molecular biology. CIMMYT and other IARCs would act as a clearinghouse or broker for programs in developing countries that would like to try some of these techniques or learn more about them. This is particularly helpful to a country with a small breeding program that is struggling to support its conventional work let alone embark upon the use of expensive molecular biology techniques.

Micronutrients—There are many ideas in this area that might include networking possibilities.

Group Discussion

Philosophy of networking

It was agreed that the philosophy regarding networks was sound and should be further pursued. The capacity of

national programs to participate fully in networks has increased greatly over the years, but it was felt that even in networks involving advanced programs, CIMMYT could still play a useful coordination role by bringing together scientists with similar interests and helping with selection of key testing locations.

Particular mention was made of the wheat crop management training course for Latin American agronomists scheduled to begin in Argentina in 1991. CIMMYT catalyzed the program, was involved in helping Argentina obtain funding, will be assisting in the first 1-2 years of the course's curriculum development, and will be also be involved in identifying training candidates. This represents something of a milestone—a decentralized activity in the hands of a national program, but existing for the benefit of an entire region. It will provide an example for future activities.

Mention was also made of networking activities where CIMMYT has no coordination role—these include the Septoria Network (the Netherlands takes the lead role), which has been functional for the past 10 years and the Helminthosporium Network mentioned earlier with collaboration between Germany, Brazil, and Israel. CIMMYT collaborates in these programs and acts as a facilitator for contacts with a wider group of national programs.

This prompted the question of the future role of CIMMYT--will it continue as basically a breeding organization or will it become a general research organization on wheat addressing the miriad of research topics that were mentioned in the introduction above. General research would represent a major shift in policy.

It was stressed that CIMMYT will continue as a center for producing germplasm although the germplasm product may change somewhat. It was agreed that there may be reasons to shift policy for crop management research—in the past, there were scarcities of trained personnel in many countries and CIMMYT formed very close (often bilateral) associations with programs to formulate the research agendas. This situation has changed today and thus dictates changes within CIMMYT.

It was questioned whether networking alone was sufficient to support the wheat research efforts of national programs, particularly those where wheat is only just now emerging as a viable crop option. It was pointed out that the most important thing initially in these countries is to identify biotic and abiotic constraints to local wheat production. This type of work may require more specific consultations by CIMMYT staff and others. Following the identification of constraints, networking could be a cost-effective manner of approaching the problem through collaboration with countries or areas with similarly defined problems or with those institutions that have basic expertise in those subjects. The organization of such activities could be facilitated through CIMMYT.

A basic role of networking is information dissemination. In many countries, research literature from other wheat programs is unavailable due to the lack of international journals or, more importantly, the lack of written reports on research carried out. Networks allow informal reporting between countries.

Futher networking possibilities

Breeding—It was suggested that an international yield trial for adaptability for warmer areas be instituted. This was supported as a method of distributing germplasm from national programs in addition to warm climate wheats developed at CIMMYT.

Another suggested network activity was the development of sprouting resistant germplasm—this appears to be of potential importance for areas of Asia, Africa, and South America.

The idea that CIMMYT should act as the filter for new biotechnologies for dissemination to national programs was well supported.

Disease resistance—Since tanspot is increasing in importance, particularly in South America where the adoption of zero tillage is becoming popular, GTZ has been approached for funding research on this disease as an adjunct to the existing spot blotch network between Germany, Brazil, Israel, and CIMMYT. Methodologies for spot blotch and tanspot are comparable.

There was some concern expressed regarding the lack of emphasis on the rust diseases in the existing networks. Fears were expressed that if selection pressure for these diseases is relaxed, achieved gains might be lost. It was stressed that to CIMMYT, at least, leaf rust is one of the most important disease priorities for the warm areas. It is assumed that the International Bread Wheat Screening Nursery will remain the major vehicle for distribution of new gene combinations for rust resistance.

However, there were further concerns on the amount of rust research on a global scale. Data returned on disease incidence and severity, rusts included, are not always reliable. It seems that those scientists trained in regional and in-country pathology workshops of some 10 years ago have now moved on to other positions and have been replaced by young scientists with little specialized pathology training. Thus, it was suggested that the workshops, on a regional basis, be revived—this would be a type of network activity and would fit well with the evolving plans of CIMMYT, i.e., to decentralize training.

As the importance of soilborne diseases is becoming more clearly defined, it was suggested this could form the basis of a network—most countries have little experience with soilborne diseases in wheat.

Aphid resistance—The greenbug and other aphids are becoming rather important in the Middle East, North Africa, and the warm areas of South America. The expertise already developed at Oklahoma State University and in the Southern Cone of South America offers an excellent foundation for a collaborative network with national programs and IARCs (ICARDA, CIMMYT) to develop aphid-resistant germplasm.

Conclusion

There was a general consensus that the experiences with networks had been good and that this form of activity should be expanded. In particular, some national program representatives expressed their inabilities to fully investigate the newly developed biotechnologies—this may potentially be one of the most important networking issues in the coming years. Informal information dissemination should remain a top priority within all networks.

Durable Leaf Rust Resistance in Wheat in Brazil

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Abstract

*The existence of a favorable environment for wheat leaf rust and the continuous growth and variability of the pathogen (*Puccinia recondita *f.sp.* tritici*) in Brazil present a challenge to those breeding wheat for resistance to the disease. Concerning resistance durability, there are extreme differences among Brazilian cultivars. This poster briefly discusses the following points:*

- *Durable resistance conferred by the adult plant gene* Lr13 *in combination with* Lr34 *was probably present in Alfredo Chaves, a Brazilian landrace.*
- *The level of Frontana resistance must be improved upon.*
- *Backcrossing or other breeding methods may add Lr genes and improve the durable resistance conditioned by* Lr13 + Lr34.
- *Polysu adult plant resistance is still efficient in field trials.*

Introduction

Most of the traditional wheat areas of Brazil provide a favorable environment for wheat leaf rust development. The continuous growth and variability of the pathogen (*Puccinia recondita* f.sp. *tritici*) in Brazil, where one to three new leaf rust races are normally detected each year, present a formidable challenge to those breeding wheat for resistance to the disease. There are huge differences in resistance durability among Brazilian cultivars (Table 1).

Durable Resistance Conferred by *Lr13* and *Lr 34*

These genes were probably present in the Brazilian landrace Alfredo Chaves (Roelfs 1988). In 1989, of Brazilian wheats that have been recommended for more than 3 years, 34% of the cultivars have a coefficient of infection (CI) less than 10. Most of these a[illegible]r to carry *Lr13* (Table 2).

Durable Resistance in Brazilian Cultivars

The level of resistance conferred by the cultivar Frontana should be improved upon. Frontana, BH1146, IAC 5-Maringá, and IAS 57, released between 1940 and 1972 and still recommended today, probably descend from Polysu and/or Alfredo Chaves 6.21. INIA 66, released in 1966 and still recommended, is reported to possess *Lr13* (Pfeiffer et al. 1988). With the exception of Frontana, which has a coefficient of infection (CI) of 24.5 (49 evaluations), the CI of the oldest cultivars is greater than 40. Anahuac 75 and CNT 8, extensively cultivated for more than 10 years, may also have *Lr13* involved in their resistances. Their respective CIs, from numerous evaluations, are 3.0 and 12.4.

Backcrossing or other breeding efforts should be intensified to add other leaf rust genes to enhance the durable resistance levels conditioned by *Lr13* and *Lr34* (Table 3). Polysu adult plant

resistance could possibly play a role in this intensification. De Cunto et al. (1956) reported on this resistance source, which is still efficient today.

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Table 1. Leaf rust resistance durability and possible *Lr* genes of some Brazilian wheats.

Variety	Cross	Possible Lr gene	Durability of resistance (years)	Lr gene[a] ineffectiveness
Frontana	FRONTEIRA/MENTANA	13,34,T3[b]	>20[c]	-
Toropi	FRONTANA/QUADERNA// PETIBLANCO 8	13,+	16	-
Jacuí	COLOTANA 824.51/YAKTANA 54/CARAZINHO/3/TOROPI	13,+	15	-
Anahuac 75	II 12.300//LERMA ROJO 64/SIETE CERROS /5/NORTEÑO 67	10,13,17	15[c]	-
CNT 8	IAS 20/NORTH DAKOTA 81	13,+	14[c]	-
Trigo BR 4	IAS 20*3/SINVACHO GAMA	13,+	11[c]	-
Trigo BR 14	IAS 63/ALONDRA SIB// GABOTO/LAGOA VERMELHA	26,34, and/ or T3, 13+[d]	5[c]	-
Tifton	GA 1123/3/N 10 B/TENMARQ //2*HADDEN/4/CI 13524/ ASOSAN//PURDUE 5714B.3. 11.3	24	1	24
CEP 14-Tapes	PEL 72380/ARTHUR 71	9	1[c]	9
Alondra	D 6301/NAINARI 60//WRM /3/CIANO*2/CHRIS	26,+	Became susceptible before release	26

[a] Trigo BR 14, Tifton, CEP 14-Tapes, and Alondra were resistant to all known pathotypes. Virulence on Trigo Br 14 was first detected in 1989. Seedlings are susceptible. Preliminary data under growth chamber conditions indicate the probable resistance at more advanced development stages.

[b] From Roelfs (1988).

[c] Still commercial.

[d] Roelfs (unpublished)

Table 2. Possible sources of leaf rust resistance from the most resistant Brazilian cultivars recommended for more than 3 years.[a]

Possible source of resistance	*Lr* gene
Alfredo Chaves 6.21	13,+[b]
Ciano 67	13,+[b]
Frontana	13,34,T3[b]
Inia 66	13[c]
Klein Rendidor	13,+[b]
Polysu	-
Sinvalocho	13,+[b]

[a] 80% of the Brazilian cultivars that have been recommended for more than 3 years that express a coefficient of infection <10 in 1989 and possibly carry the adult plant resistance gene *Lr13*, based on ancestry.
[b] From Roelfs (1988).

Table 3. Areas under leaf rust progress curve of Brazilian wheat cultivars artificially infected in Passo Fundo, Brazil, from 1982 to 1988.

Cultivar	Year released	Probable source of resistance	Area under leaf rust progress curve[a]						
			1982	1983	1984	1985	1986	1987	1988
Trigo BR 14	1985	Alondra'S' + Frontana and/or Polysu, Sinvalocho	-	-	-	2	22	0	9
Trigo BR 35	1989	Hadden + Frontana and/or Polysu	-	-	-	-	-	14	52
CEP 11	1984	Hadden + Frontana and/or Polysu,+	-	-	1	28	1	23	96
Trigo BR 4	1979	Frontana + Polysu and/or Sinvalocho	11	11	5	63	43	1	2
Jacuí	1973	Frontana + Americano 44D[b]	69	565	84	100	72	-	-
CNT 8	1976	Frontana + Polysu	311	719	225	309	158	64	250
Frontana	1940	Alfredo Chaves 6.21	680	1065	197	472	222	-	-
Susceptible check			998	1323	659	1311	719	480	557

[a] All leaves of 10 plants from the three central of five 1-m rows were evaluated since the first symptoms. The evaluation frequency varied depending on the cycle of the cultivars: 3 or 4 in 1982, 9 to 12 in 1983, 7 to 10 in 1984 and 1985, 6 to 9 in 1986, 7 to 9 in 1987, and 6 to 8 in 1988.
[b] Americano 44D, selected from a land cultivar in Uruguay, probably includes *Lr12* and/or *Lr13* and *Lr34* (Roelfs 1988).

Resumen

*La existencia de un ambiente favorable para la roya de la hoja del trigo y el continuo desarrollo y variabilidad del agente patógeno (*Puccinia recondita *f.sp.* tritici*) en Brasil plantea un desafío a quienes realizan el mejoramiento de trigo para obtener resistencia a la enfermedad. En cuanto a la durabilidad de la resistencia, existen diferencias extremas entre las variedades brasileñas. Este trabajo analiza brevemente los siguientes puntos:*

- *La resistencia durable conferida por el gen de la planta adulta Lr13 en combinación con el Lr34 probablemente existía en Alfredo Chaves, una raza indígena brasileña.*
- *Es preciso mejorar el grado de resistencia de Frontana.*
- *El retrocruzamiento u otros métodos de mejoramiento pueden agregar genes Lr y mejorar la resistencia durable condicionada por Lr13 + Lr34.*
- *La resistencia de planta adulta de Polysu aún es eficiente en los ensayos en los campos.*

Bacterial Sheath Brown Rot Caused by *Pseudomonas fuscovaginae* in Wheat

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Abstract

Pseudomonas fuscovaginae *causes bacterial brown sheath rot in wheat during the rainy season in the Mexican highlands. The disease becomes more apparent at booting and is characterized by reduction of ear exertion. This poster presents the major identification tests of the pathogen. Ten bread wheat genotypes were planted at three different dates in Toluca, Mexico, and were inoculated with a* P. fuscovaginae *strain. Results showed significant differences in ear exertion and suggested that inoculation was more effective for late plantings. Yields of the compared genotypes were not determined only by disease severity. Data showed high variation, suggesting that more research is needed to understand the requirements of the pathogen to induce symptoms and to better standardize screening methods.*

Distribution and Environmental Conditions

Pseudomonas fuscovaginae Miyajima, Tanii and Akita nom. rev. 1983 was first identified as the causal agent of bacterial sheath brown rot (BSBR) of rice in northern Japan (Miyajima et al. 1983). In 1987, *P. fuscovaginae* was identified in Mexico as the causal agent of BSBR symptoms on wheat above 2300 masl (Duveiller and Maraite 1990). The disease is found during the rainy season (May-Nov.) when wheat is at the booting stage. The incidence in farmers' fields is below 0.1%, but in experiment stations, some genotypes show more severe infection. *Pseudomonas fuscovaginae* is an ubiquitous, opportunistic pathogen that requires a cereal crop at a susceptible stage (booting), the presence of a sufficient amount of inoculum, high humidity, and low night temperatures. The disease may affect bread wheat, durum wheat, and triticale.

Symptoms and Identification of the Bacterium

In the field, symptoms include angular blackish-brown lesions on leaf sheaths and are most obvious on flag leaf sheaths. If infection is early or severe, poor ear emergence and sterility are observed. Lesions are irregular, 10 to 20 cm in length, and bordered by a purple black area of about 2 mm. The center of old lesions appears grayish and dry.

The isolation of *P. fuscovaginae*, a fluorescent bacterium, is preferably done on KB medium and is sometimes difficult due to the frequent occurrence in lesions, of fast growing saprophytic fluorescent *Pseudomonas*. Those saprophytic bacteria are strictly aerobic, Kovac oxidase and arginine dihydrolase positive, like *P. fuscovaginae*. However, *P. fuscovaginae* can be differentiated by only few other biochemical tests. *P. fuscovaginae* does not produce 2-ketogluconate and is characterized by the simultaneous occurrence of acid production from trehalose, but not from inositol (Duveiller

et al. 1988). All *P. fuscovaginae* strains from wheat do react with the anti-*P. fuscovaginae* antiserum, produced against the HMB266 reference strain from rice. In pathogenicity tests on young wheat plants inoculated at the five-leaf stage, a typical rot of the leaf sheaths and collapse of the entire plant can be seen after 5 days of incubation in a humid room; later however, new tillers will grow again.

Comparison of Wheat Genotypes

In 1987 at CIMMYT's Toluca, Mexico, experiment station, some varieties such as Anahuac and Seri appeared more severely infected. A preliminary experiment to analyze differences of susceptibility to the disease was conducted in 1989 at the same location; 10 bread wheat genotypes were compared. Plants were sown on May 22, May 31, and June 8, 1989, in 2-m rows. At the booting stage, before flag leaf sheath opening, 10 tillers were inoculated with a concentrated bacterial suspension of *P. fuscovaginae* adjusted in the field to 10^9 Colony Forming Units (CFU)/ml, with the help of a portable spectophotometer (Spectronic Milton Roy, Mini 20). Three weeks after inoculation, the ear exertion percentage was appraised. For each tiller, 100% exertion = peduncle visible; 0% = ear staying in the boot due to severe BSBR. At harvest, the yield of each spike was recorded.

Results (Table 1) were characterized by a very high variation among data, which were transformed for statistical analysis. Significant differences between genotypes and planting dates were observed. The overall average exertion percentages were 64.8, 65.5, and 45.3%, for May 22, May 31,

Table 1. Average percentage of ear exertion (three planting dates) on 10 bread wheat genotypes inoculated at booting stage with a 10^9 CFU/ml suspension of *P. fuscovaginae* (wheat reference strain CFBP3078), in Toluca, Mexico.

Genotype	Ear exertion (%)	arcsin[a]	Yield (g)	arcsin
Anahuac	77.5	140.0a[b]	1.98	15.9ab
Alondra	69.2	122.0ab	2.26	17.1ab
Pavon	69.2	121.0ab	1.61	14.1ab
Chuan Mai #18	60.0	109.0ab	1.98	15.9ab
Anza	60.0	110.0ab	1.03	11.2b
Thornbird	55.0	105.0ab	1.22	12.0a
Seri	55.0	99.0ab	1.62	14.5ab
Shanghai 7	48.3	91.0b	1.36	12.4ab
Kauz'S'	46.7	87.0b	1.79	15.3ab
Shanghai 8	44.2	85.0b	1.37	12.6ab
CV		45.9%		23.5%
F tests:				
Genotypes (9-270 df)		3.78 **[c]		10.61 **
Date (2-270 df)		11.63 **		5.60 **
Interaction (2-18 df)		1.43		2.66 **

[a] 2 arcsin √(X/100).
[b] LSD (P=0.05); genotypes with same letter are similar.
[c] ** P = 0.01.

and June 8, respectively. This suggests that inoculation was more effective for the late planting, perhaps because of cooler night temperatures. Factors other than BSBR also determined the yield of genotypes compared in this study. A significant genotype-planting date interaction was observed for yield. Anahuac, which was apparently severely infected in 1987, had the best score in 1989.

Discussion

The high variation among single ears analyzed under artificial inoculation conditions suggests that more research is needed to understand the precise requirements of the bacterium to induce the disease and to better standardize screening methods.

Regarding rice, the booting stage should further be characterized. Studies on the epidemiology of bacterial sheath brown rot of wheat are difficult to conduct due to the low incidence of the disease. In the field, no more than one infected tiller per plant is usually observed under natural conditions. Nevertheless, the analysis of conditions conducive to BSBR development should be done to avoid the release of susceptible wheat genotypes in disease-prone locations so that *P. fuscovaginae* does not evolve from a minor pathogen to a major constraint, as it has in irrigated or swamp rice at high altitudes.

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Resumen

Pseudomonas fuscovaginae *causa la pudrición bacteriana de la vaina del trigo durante la estación de lluvias en las tierras altas de México. La enfermedad se vuelve más evidente en el embuchamiento y se caracteriza por la reducción de la salida de la espiga. Este trabajo presenta las principales pruebas de identificación del agente patógeno. Se sembraron 10 genotipos de trigo harinero en tres fechas diferentes en Toluca, México, y se los inoculó con una cepa de* P. fuscovaginae. *Los resultados mostraron diferencias considerables en la salida de la espiga e indicaron que la inoculación fue más eficaz en las siembras tardías. Los rendimientos de los genotipos comparados no fueron determinados sólo por la severidad de la enfermedad. Los datos mostraron una gran variación, que señala que se necesitan más investigaciones con el fin de conocer lo que requiere el agente patógeno para inducir los síntomas, y con el propósito de estandarizar mejor los métodos de examen.*

Progress in Developing Bread Wheats Resistant to *Helminthosporium sativum*

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Abstract

Helminthosporium sativum *P.K. and B. (Syn.* Bipolaris sorokiniana *Sacc. et Sorokin) is an important pathogen that limits wheat production in many nontraditional warmer areas. Resistance to leaf (spot blotch), node, and grain infection (black point) in semidwarf wheats has been limited. Advanced lines derived from the China/CIMMYT shuttle breeding program and two check cultivars were evaluated under field conditions to estimate the progress being made. Results suggest the existence of different genetic mechanisms of resistance. The recognition and combination of these components in future breeding efforts might further increase resistance to* H. sativum.

Introduction

Helminthosporium sativum P.K. and B. (Syn. *Bipolaris sorokiniana* Sacc. et Sorokin) is an important pathogen that limits wheat production in many nontraditional warmer areas. Resistance to leaf (spot blotch), node, and grain infection (black point) in semidwarf wheats is currently limited. In an effort to improve this situation, germplasm from China possessing resistance to *H. sativum* was crossed with CIMMYT semidwarf wheats to develop germplasm with improved yield potential and adequate resistance. Advanced lines derived from this breeding program and two check cultivars were evaluated under field conditions to estimate the progress achieved.

Materials and Methods

Six advanced lines and two check cultivars (Table 1) were grown in a split plot design (replications = 4; main plot =

Table 1. Cultivar name or cross, selection history, and origin of two check cultivars and six advanced bread wheats lines.

Cultivar Name or Cross (Selection History)	Origin
1. BH1146 (Resistant check)	Brazil
2. CIANO 79 (Susceptible check)	CIMMYT-Mexico
3. Fufan/Veery #5 CM88930-10Y-0M-0Y-2M-4Y-0B	China/CIMMYT-Mexico
4. Fufan/Veery #5 CM88930-10Y-0M-4Y-4M-1Y-0B	China/CIMMYT-Mexico
5. Fufan/Veery #5 CM88930-10Y-0M-0Y-4M-0Y	China/CIMMYT-Mexico
6. Fufan/Veery #5 CM88930-7Y-0M-0Y-4M-8Y-0B	China/CIMMYT-Mexico
7. NANJING 82149/Lira CM91187-12Y-0M-0Y-4M-1Y-0B	China/CIMMYT Mexico
8. Flycatcher/3/Golden Valley/Azteca//Musala CM76290-32Y-04M-06Y-6B-0Y	CIMMYT-Mexico/Yugoslavia

variety; sub-plot = with or without fungicide) in Poza Rica (20°32'N, 97°26'W, 60 masl), under high natural disease incidence during the 1989-90 growing cycle. Each sub-plot consisted of six rows, 3 m long.

Fungicide-protected plots were sprayed with Procloraz at crop stages 10.5, 10.5.2, and 10.5.4 (Feekes-Large scale). Foliar disease incidence was rated utilizing a double digit scale at stages 10.5.3, 10.5.4, and 11.1. The product of both digits was used as a coefficient of infection.

Results and Discussion

Grain yield and test weight are given in Figures 1A and 1B. Significant differences ($p < 0.001$) for grain yield and test weight between the advanced lines and the two checks indicate that progress was achieved for both variables. Differences in spike infection and grain infection (Figures 1C and 1D) were significant ($p < 0.001$). The interaction between grain infection and fungicide was significant ($p < 0.05$); in contrast, the interactions of grain yield-fungicide, test weight-fungicide, and spike infection-fungicide were not significant.

Protection from the two initial fungicide applications was effective, however, from Feekes stage 10.5.4 onwards, leaf infection increased in the susceptible check, CIANO 79, and lines No. 5, 6, and 7. In these entries, grain yield and test weight (Figure 1B) were affected. In contrast, the fungicide effectively controlled the pathogen throughout the crop cycle for BH1146 (resistant check) and lines 3, 4, and 8.

Leaf damage differed significantly ($p < 0.001$) between fungicide-treated and untreated subplots with the second and third applications. The inoculum pressure in the field was high and uniform and the coefficients of infection for leaf damage (Figure 1E) were high at all stages. This might be due to the involvement of unknown interacting abiotic factor(s) with the level of infection.

Results in Figures 1C, 1D, and 1E indicate that infection of the external tissue of the spike and leaf infection are not related to seed infection. This would suggest that resistance to spike and leaf infection is independent of the genetic system controlling grain infection. Similarly, Conner (1990) could not detect a strong correlation between the two types of infection in a study involving 18 wheat cultivars. However, the effectiveness of the fungicide in controlling grain infection differed among genotypes; lines 2 and 5 even exhibited an increase in the number of grains infected. This might have been due to an extended flowering period and/or duration of green spike tissue caused by the protective effect of the fungicide, thus providing an increased period during which the fungus could infect the floret or immature grain.

In contrast to previous growing cycles, no node infection was observed with the exception of two plots of the susceptible check CIANO 79.

Conclusions

Resistance to *H. sativum* obtained from Chinese germplasm has increased grain yield performance and test weight in semidwarf wheats in the presence of the pathogen. Results obtained under field conditions suggest the existence of different genetic mechanisms of resistance. The recognition and combination of these components in future breeding efforts might further increase resistance to *H. sativum*

Reference

Conner, R.L. 1990. Interrelationship of cultivar reaction to common root rot, black point and spot blotch in spring wheat. Plant Disease 74(3):224-227.

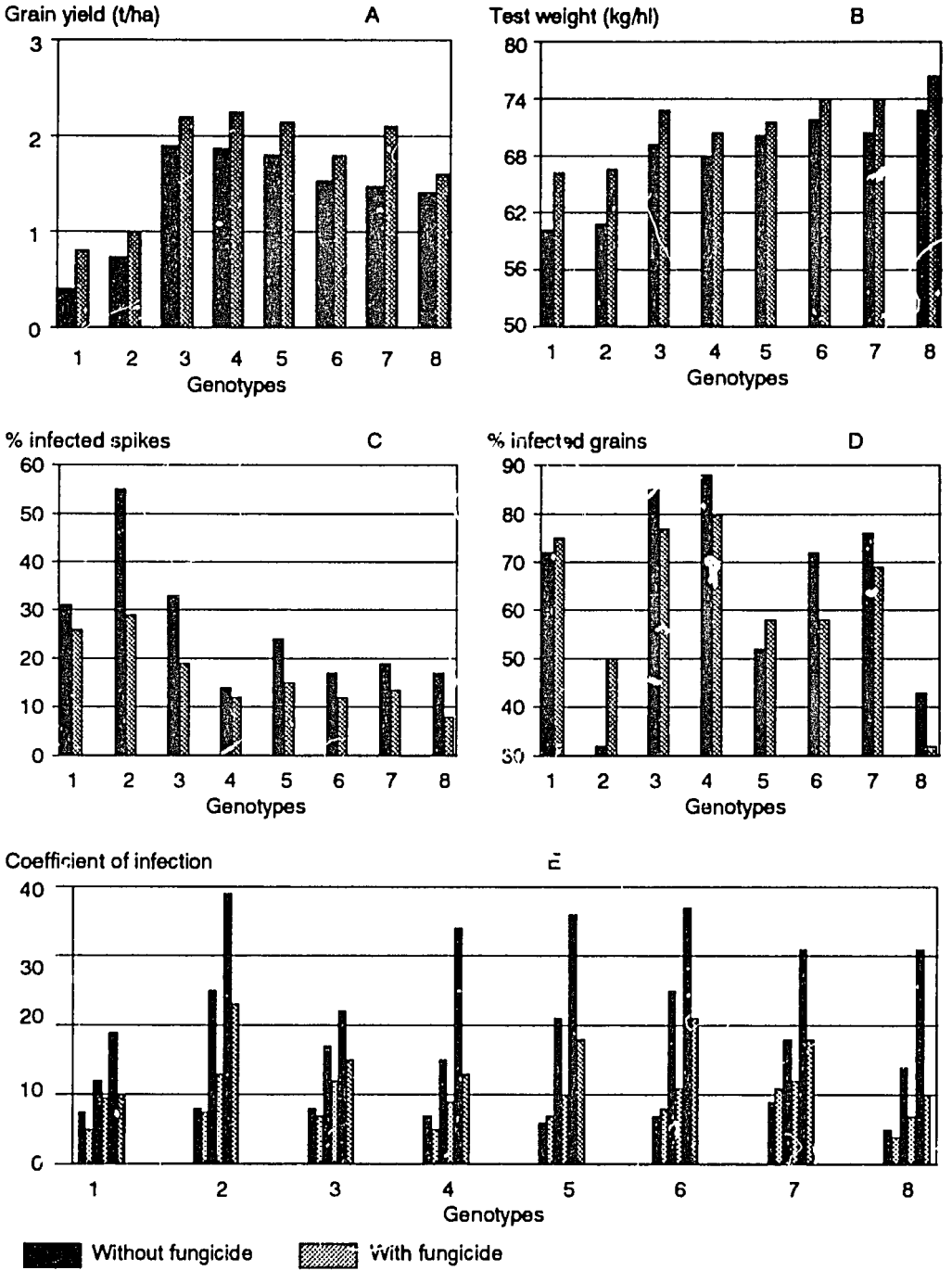

Figure 1A-E): A) grain yield (t/ha); B) test weight (kg/hl); C) percentage of infected spikes; D) percentage of infected grains; and E) coefficient of infection for leaf damage at three different growth stages (Feekes 10.5.3, 10.5.4, and 11.1) of six bread wheat advanced lines and two standard checks (See Table 1 for line names and origin). Poza Rica, Mexico, 1989-90.

Resumen

Helminthosporium sativum *es un importante agente patógeno que limita la producción de trigo en muchas zonas cálidas no tradicionales. Ha sido limitada la resistencia a la infección de la hoja (tizón foliar), del nudo y del grano (punta negra) de los trigos semienanos. Se evaluaron líneas avanzadas derivadas del programa de mejoramiento alternado entre China y el CIMMYT y dos variedades testigo en condiciones de campo, con el fin de estimar el progreso alcanzado. Los resultados indican la existencia de diferentes mecanismos genéticos de la resistencia. El reconocimiento y la combinación de estos componentes en futuras actividades de mejoramiento podría incrementar más la resistencia a* H. sativum.

Resistance to *Helminthosporium sativum* in Bread Wheat: Relationship of Infected Plant Parts and the Association of Agronomic Traits

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Abstract

This poster reports results on the infection of Helminthosporium sativum *(Syn.* Bipolaris sorokiniana*) on different plant parts (roots, leaves, nodes, spikes, grains) and these parts' association with agronomic and physiological traits in 87 advanced bread wheat lines developed at CIMMYT. Two types of resistance mechanisms were operative and their combination offers the possibility to develop bread wheat germplasm with increased overall resistance to* H. sativum *and hence better performance and adaptation of wheat in nontraditional, warmer areas.*

Introduction

Helminthosporium sativum (Syn. *Bipolaris sorokiniana*) can attack seedlings, roots, leaves, nodes, spikes, and grains during the various stages of plant development. To guide future breeding efforts, it will be necessary to identify the mechanism of general (overall) resistance through the quantification of individual plant parts affected and to examine the associations and interactions among them, as well as their associations with agronomic traits such as grain yield and test weight.

Conner (1990) examined the relationship among common root rot, grain infection (black point), and leaf infection (spot blotch) in 18 bread wheat cultivars and reported large differences in disease reactions for each disease component. None of the cultivars were resistant to all three disease components. In a study with barley, Clark (1966) obtained similar results. He determined that there was no apparent relationship between root rot and head blight resistance, since none of the barleys showed good resistance to both.

The objective of this study was to investigate the relationship among the different plant parts that are infected by *H. sativum* and their associations with agronomic and physiological traits in 87 advanced bread wheat lines developed at CIMMYT.

Materials and Methods

The 87 advanced bread wheat lines used in the study came from the Third Warmer Area Wheat Screening Nursery. These were planted in 2-row, 5-m plots during the 1989-90 growing cycle at Poza Rica, Mexico, an environment with high natural disease incidence.

Notes and data were taken for:

- Leaf damage at 10.5.3, 10.5.4, and 11.1 Feekes-Large stages. Damage was scored using a double-digit scale and transformed to an infection coefficient (product of both digits).
- Spike damage (%).
- Infected grain (%).
- Grainfill duration: days from spike emergence to maturity (days).

- Days to spike emergence.
- Days to flowering.
- Days to maturity.
- Plant height (cm).
- Thousand grain weight (TGW) (g).
- Test weight (kg/hl).
- Grain yield (kg/ha).

Phenotypic correlation estimates were obtained using the CORR procedures of SAS (1985).

Results and Discussion

Correlation coefficients between disease scores and physiological and agronomic traits (Table 1) were either not significant or low. Genotypes with short plant height had slightly higher leaf disease scores at Feekes-Large stage 11.1, and late flowering genotypes had slightly higher infection at Feekes 10.5.4. Grainfill duration and days to maturity, two related traits (r=.65**), were associated with leaf damage at Feekes-Large 11.1, spike damage, and grain damage. Genotypes with a short grainfill duration had significantly higher leaf and spike damage, but lower grain damage compared with genotypes with long grainfill durations. Further, early maturing genotypes had lower grain damage, but higher leaf and spike damage than late-maturing genotypes.

Yield, TGW, and test weight were negatively associated with leaf and spike infections, but not with grain infection (Table 2). In contrast to grain yield and test weight reductions, which showed closer associations with disease incidence at a later stage of crop development (Feekes-Large 11.1), reduction in TGW was more closely associated with disease scores at Feekes-Large 10.5.3.

Since leaf damage at all stages was associated with spike damage (Table 3), the higher correlation coefficients between yield and leaf damage at Feekes-Large 11.1 might be due to the combined effect of both components of the disease.

Leaf damage scores at different growth stages were positively correlated, but coefficients of correlation were relatively low.

The lack of significant associations among grain infection and leaf or spike infection at three different physiological stages (Table 3) suggests the existence of a resistance mechanism for leaf and spike infections, which is independent of the mechanism for resistance to grain infection, and confirms the results obtained by Clark (1966) and Conner (1990). However, Raemaekers (1987) reported significant correlations among vertical spread of spot blotch, spot blotch severity on the flag leaf, head blight severity, and black point. In his experiment, *Fusarium* spp., *Xanthomonas campestris*, *Fusarium equiseti*, and *Phoma sorghina* were still present in grain samples even after the elimination of fusarium-infected grains. Hence, in addition to differences in scoring methodology, pathogens other than *H. sativum* and/or interactions between these pathogens and *H. sativum* may have caused contrasting results.

Conclusions

The identification of sources of resistance for both types of resistance mechanisms and their combination offer the possibility to develop bread wheat germplasm with increased overall resistance to *H. sativum* and, hence, better performance and adaptation of wheat in nontraditional, warmer areas.

Table 1. Phenotypic correlations of leaf infection at three stages, spike infection, and grain infection with plant height, grainfill, days to maturity, days to flowering, and days to spike emergence.

	Leaf infection[a]			Spike infection	Grain infection
	10.5.3	10.5.4	11.1		
Plant height	-0.11	-0.09	-0.27*	-0.07	0.19
Grainfill	-0.26	-0.25	-0.29*	-0.42**	0.31*
Days to maturity	-0.006	0.11	0.39*	-0.42**	0.33*
Days to flowering	0.18	0.33*	-0.24	-0.16	0.09
Days to spike emergence	0.25	0.40**	-0.23	-0.13	0.13

[a] Feekes-Large scale.

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

Table 2. Phenotypic correlations of leaf infections at three different stages, spike infection and grain infection with yield, thousand grain weight, and test weight.

Disease components	Feekes-Large stage	Yield	Thousand grain weight	Test weight
Leaf Infection	10.5.3	-0.44**	-0.63**	-0.45**
Leaf Infection	10.5.4	-0.38**	-0.46**	-0.30*
Leaf Infection	11.1	-0.68**	-0.47**	-0.48**
Spike Infection	11.1	-0.46**	-0.40**	-0.54**
Grain Infection	11.4	0.01	-0.09	-0.04

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

Table 3. Phenotypic correlations of disease scores for different plant parts affected by *H. sativum*: leaf damage at stages 10.5.3, 10.5.4, and 11.1 (Feekes-Large) and spike and grain infection.

	Growth stage	Leaf damage			Grain infection
		10.5.3	10.5.4	11.1	
Leaf damage	10.5.3		0.52**	0.46**	0.14
	10.5.4	0.52**		0.35**	0.16
	11.1	0.46**			0.03
Spike infection	11.1			0.56**	0.17

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

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Resumen

Este trabajo describe los resultados de la infección con Helminthosporium sativum *(sin.* Bipolaris sorokiniana*) en distintas partes de la planta (raíces, hojas, nudos, espigas, granos) y la relación de estas partes con las características agronómicas y fisiológicas en 87 líneas avanzadas de trigo harinero desarrolladas en el CIMMYT. Entraron en juego dos tipos de mecanismos de resistencia, y al combinación de ellos ofrece la posibilidad de generar germoplasma de trigo harinero que tenga una mejor resistencia general a H. sativum y, por tanto, muestre un mejor comportamiento y adaptación en zonas cálidas donde el trigo no es un cultivo tradicional.*

Development of Wheat Germplasm Resistant to Fusarium Head Blight (*Fusarium graminearum*)

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Abstract

*During the 1980s, a network for development and testing of scab (*Fusarium graminearum*)-resistant germplasm was created to serve as a mechanism for exchanging information and distributing wheat germplasm. The identification of scab-resistant wheats in China initiated a shuttle breeding program between China and CIMMYT/Mexico. Shuttling of scab-resistant material between CIMMYT/Mexico and Paraguay also commenced in 1980s. Materials from these shuttles have been distributed worldwide in international nurseries. International funding for Southern Cone Scab Networking in the future has been proposed. A similar funding proposal for global scab networking is lacking.*

One objective of breeding for wide adaptation is the development of wheat germplasm that is resistant to fusarium head blight (scab) caused by *Fusarium graminearum*. In recent years, a network for development and testing of scab-resistant germplasm (Figure 1) has been used as a mechanism for exchanging information and germplasm. China, Paraguay, Argentina, Brazil, Uruguay, Canada, and CIMMYT/Mexico have been especially involved.

The identification of scab-resistant Chinese wheats over the last 10 years has played a key role in the initiation and execution of a shuttle breeding effort between China and CIMMYT/Mexico. An additional shuttle between CIMMYT/Mexico and Paraguay has helped accelerate progress in the development of scab-resistant germplasm.

Throughout the 1980s, many scab-resistant lines and varieties were introduced regularly into the CIMMYT program. This material was characterized agronomically and then crossed with CIMMYT material. During this same period, several screening techniques from China were adopted and new ones were developed. Since 1985, many international nurseries have been distributed throughout the world to reinforce the networking effort (Tables 1 and 2).

Future work will involve genetic analysis of resistance and a search for other sources of resistant germplasm involving wide crosses. A proposal for international funding has been presented to the Cooperative Research Program of the Southern Cone (PROCISUR) for the possible creation of a germplasm development program and a scab network among Southern Cone countries. This, along with funding for a global network, would be a unique program that would help bring attention to the economic importance of the disease as well as accelerate the scab resistance efforts.

Table 1. Distribution of advanced lines through international nurseries.

Year	Origin of nurseries	Number of countries by continent					
		Africa	Asia	Europe	North America	South America	Others
	CIMMYT/Mexico						
1985-86	1st SRSN	4(6)	4(9)	5(7)	3(6)	4	2
1986-87	2nd SRSN	5(6)	3(4)	7(8)	3(8)	6(18)	5
	Advanced lines, Yangtze	10(13)	3(4)	3	1(2)	11(29)	6
1987-88	3rd SRSN	3	7(18)	9(11)	2(8)	8(16)	13(17)
	CIMMYT/Paraguay						
1990	4th SRSN		2(3)	3	2	1(2)	
	PC Scab		1(5)	2	2	2(3)	

SRSN = Scab Resistance Screening Nursery; PC = small seed multiplication plot.
Number of sites in parentheses.

Table 2. International distribution of segregating populations.

Year	Origin of nurseries	Number of countries by continent					
		Africa	Asia	Europe	North America	South America	Others
	CIMMYT/Mexico						
1986-87	F_2 Scab	3(4)	3(4)			6(15)	1
1987-88	F_2 Scab	7(8)	4(9)	2(3)	1	5(9)	3
	F_4 Scab	7(8)	3(14)	6(7)		5(9)	2
1988-89	F_2 Scab	4	4(10)	8(10)	2	5(13)	1
	CIMMYT/Paraguay						
1990	F_4 Scab	1	1(4)	1	1	2	
	F_5 Scab		1(2)	1		3	
	F_6 Scab	1	1(3)	2	2	2(3)	

Number of sites in parentheses.

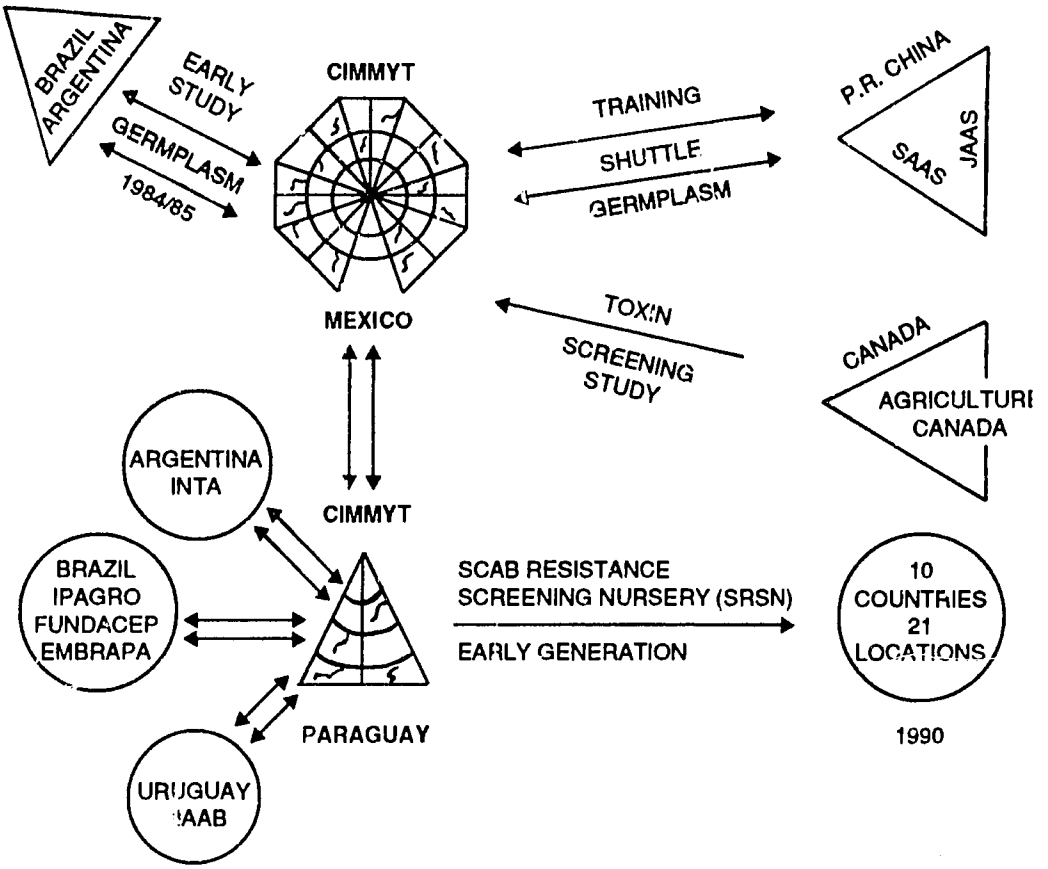

Figure 1. Network for development and testing of scab-resistant germplasm and transfer of information. CIAAB = Centro de Investigaciones Agrócolas "Alberto Boerger", Uruguay; EMBRAPA = Brazilian Agricultural Research Enterprise, Brazil; FUNDACEP = Federation of Wheat and Soybean Cooperatives, Rio Grande do Sul, Brazil; INTA = National Institute of Agricultural Technology, Argentina; IPAGRO = Institute of Agriculture and Livestock Research, Rio Grande do Sul, Brazil; JAAS = Jiangsu Academy of Agricultural Sciences, China; SAAS = Shanghai Academy of Agricultural Sciences, China.

Resumen

Durante el decenio de los 80, se creó una red para generar y ensayar germoplasma resistente a la roña (causada por Fusarium graminearum*), con el fin de que sirviera como mecanismo para intercambiar información y distribuir el germoplasma de trigo. La identificación de trigos resistentes a la roña en China permitió iniciar un programa de mejoramiento alternado entre China y el CIMMYT en México. En ese mismo decenio también comenzó el mejoramiento alternado de material resistente a la roña entre el CIMMYT en México y Paraguay. Los materiales obtenidos en esta labor han sido distribuidos en todo el mundo mediante viveros internacionales. Se ha propuesto el financiamiento internacional de la red de la roña en el Cono Sur en el futuro; sin embargo, no se ha propuesto un financiamiento similar para una red mundial.*

Update on Wheat Blast (*Pyricularia oryzae*) in Brazil

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* Did not attend the conference.

Abstract

Wheat blast caused by Pyricularia oryzae *was identified in Brazil in 1985 in northern Paraná. The disease incidence in the first year was sporadic, but in the following year, it spread to northern and western Paraná, northwestern São Paulo and southern Mato Grosso do Sul. In 1988, it was also reported from Lagoa Vermelha and Passo Fundo in Rio Grande do Sul. In Paraná, it was most severe on farms located along the Paranapanema, Tibagi, Ivaí, and Piquiri Rivers. Losses varied from negligible to total. The highest damage was observed when infection occurred in the rachis, which limited grain development, resulting in partial damage or death of the head above the point of infection. No control measure has yet allowed an adequate level of disease reduction, but research has shown that mancozeb + tricyclazole, mancozeb + fentin hydroxide, and mancozeb + benzimidazole—when applied preventively (one or two sprays) before rain and during heading—can reduce head infection by 50 to 70%.*

History and Geographical Distribution

Wheat blast, caused by *Pyricularia oryzae*, was first identified in Brazil in 1985 in seven counties of northern Paraná. In 1986, it had spread to 27 counties in northern and western Paraná causing severe losses on some farms. That same year, it was also found in northwestern São Paulo State and southern Mato Grosso do Sul, although economic damage was negligible. In 1987, the disease was found in 70 counties in northern and western Paraná where it caused complete crop failures primarily in areas located near dams and river valleys and sown before April 10. In 1988, in contrast to previous years, blast development began 10 to 15 days after emergence, which resulted in death of seedlings in many fields.

A disease survey conducted in 1988 showed that the wheat blast had spread to more than 100 counties in northern and western Paraná, with disease severity ranging from a trace to 100% infection. In October 1988, the disease was first reported to be present at Lagoa Vermelha and Passo Fundo in Rio Grande do Sul (Picinini 1988). In 1989 because of reduced rainfall and low temperatures during the period from sowing to early heading, wheat blast development was very low. Nevertheless, when late sowing (May to June) caused heading to coincide with frequent rains and rising temperatures, wheat blast incidence increased but losses were insignificant.

Symptoms

The most conspicuous symptom of wheat blast is head infection, but infection can be found on all above-ground plant parts (Figure 1A-F). On the leaves, the lesions vary in shape and size, depending on the age of the plant. Young leaves infected up to 35-40 days following emergence (Figure 1A) show elliptical lesions very similar to rice blast. Under favorable conditions, seedling infection can be very severe and can result in plant death. As plants grow older, leaf lesions are not as conspicuous in that they are less frequent and

narrower (Figure 1B). The lesions on both young and old leaves have a white center and a reddish-brown margin on the sunny side of the leaf and are dark gray on the underside where sporulation occurs (Figure 1C).

Lesions on the sheath, culm, and neck are similar in size and vary in shape from elliptical to elongated; centers are whitish and narrow margins are reddish-brown (Figure 1D).

Head infection can occur on the glumes, awns, and rachis. Glume infection is characterized by elliptical lesions with a white to light-brown center and a reddish-brown to dark-gray margin. Infection of the awn results in a brown to whitish discoloration. Infection of the rachis causes partial loss to complete death of the head, depending on the point of infection. Usually, all the spikelets above the infection point on the rachis are blighted and turn white and can be clearly distinguished from the healthy part below the infection point (Figure 1E-F).

At the point of infection, the rachis initially acquires a brown to black discoloration and later turns light to dark-gray due to heavy sporulation. Depending on the growth stage when head infection occurred, grain formation can vary from nil to almost normal kernels. With late infection, grainfill will be better, but there is also a greater chance of seed infection, which favors seed transmission of the pathogen.

Varietal Resistance and Physiological Races

In 1986, two isolates of *P. oryzae* were collected from wheat varieties Anahuac and Alondra in infected fields at Sertanopolis, Paraná. They were cultured on artificial medium and inoculated on 42 wheat varieties in the greenhouse under high temperature and high humidity. Varieties CNT 8 and OCEPAR 11 were immune, whereas BH1146, IAS 57, OCEPAR 6-Flamingo, OCEPAR 12-Maitaca, CEP 8066, IAPAR 1-Mitacore, and CEP 7780 showed a low percentage of head infection (Igarashi and Utiamada 1986, Igarashi 1988b).

In 1987, several isolates obtained from regions with different climatic conditions were mixed and inoculated in the greenhouse on varieties that had previously shown low head infection and on new untested varieties. Disease readings taken 10 days after inoculation showed that all varieties were susceptible. This indicates that new races of the pathogen were present. When six isolates, following monosporic cultures, were inoculated on the japonese differential of rice varieties CICA 9 and Razza 82 and one barley variety, five races were differentiated: 314, 321, 327, 337, and 433. These races had not been found to be infecting rice in Paraná (Igarashi 1988b). Rice variety Razza 82, considered susceptible to all *P. oryzae* rice races in Paraná, did not show lesion development with any of the isolates tested. However, CICA 9, which was resistant to all known rice races, was susceptible to the wheat isolates. Barley was highly susceptible to all of the *P. oryzae* wheat isolates (Igarashi 1988b).

In research work conducted later using a higher number of isolates from different ecological regions, artificial inoculation was done using the same conditions of the previous experiment. The wheat varieties, which were initially immune or tolerant, showed susceptibility. This enforces the possibility of the occurrence of several physiological races of this fungi.

Control

Research data obtained thus far do not define adequate control of wheat blast. More information is needed on timing of fungicide application and the period of protection required. Experiments have

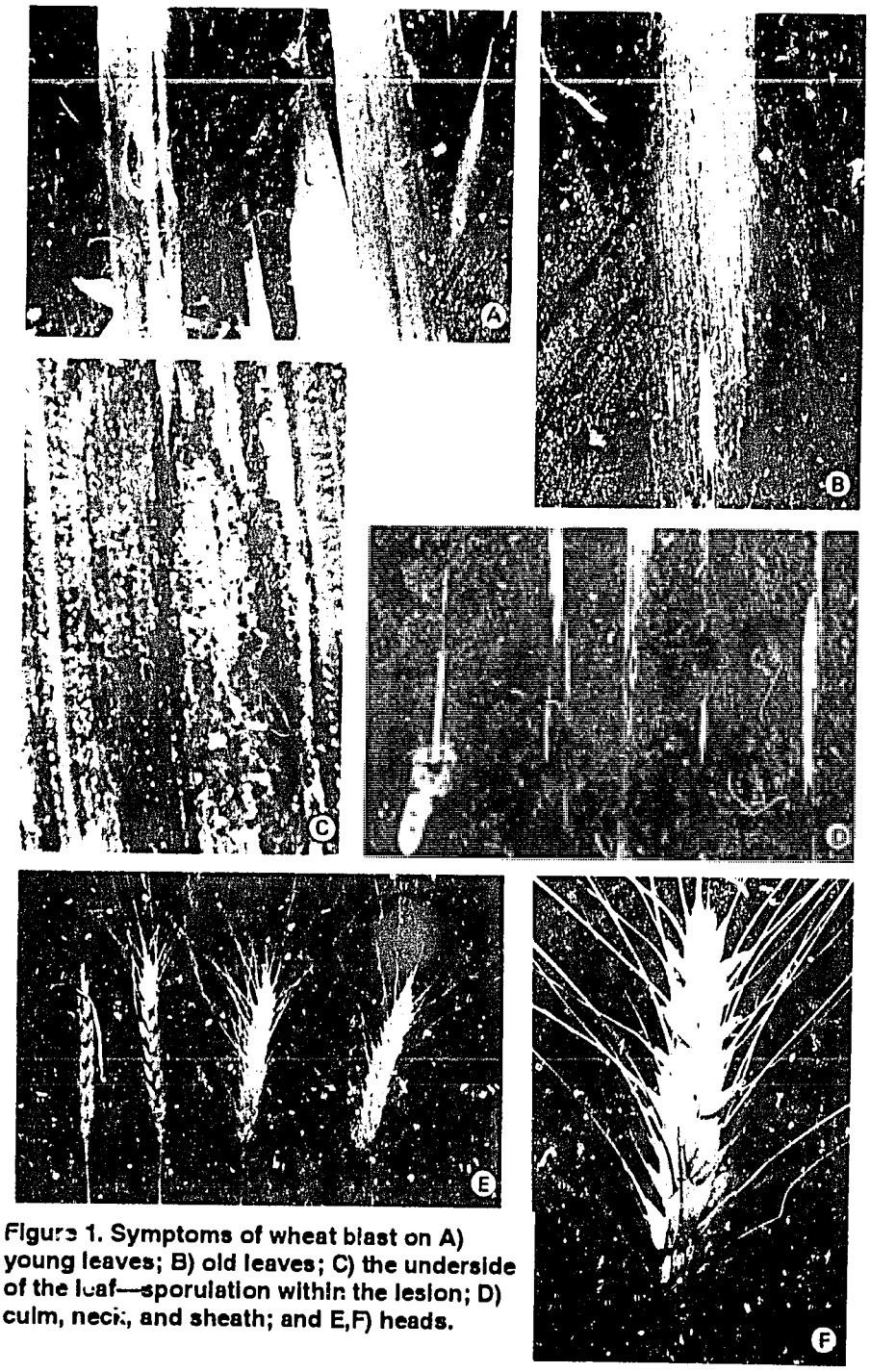

Figure 1. Symptoms of wheat blast on A) young leaves; B) old leaves; C) the underside of the leaf—sporulation within the lesion; D) culm, neck, and sheath; and E,F) heads.

shown that mancozeb + tricyclazole, mancozeb + fentin hydroxide, and mancozeb + benzimidazole can reduce head infection by 50 to 70% when applied preventively prior to rainfall and during heading followed by a second application 12 to 15 days later.

Deep plowing and elimination of volunteer plants in the following summer season are recommended as control measures aimed at reducing the amount of inoculum for the next wheat season.

Alternate hosts, especially the grass weeds, should be eliminated. Preliminary studies have shown that *P. oryzae* isolates from rice, wheat, and barley, when artificially inoculated, were pathogenic on *Avena sativa*, *Zea mays*, *Sorghum vulgare*, *Secale cereale*, *Brachiaria plantaginea*, and *Digitaria horizontalis* with varying degrees of disease development (Igarashi 1988a).

Seed treatment with iprodione (50 g ai/100 g seed) plus thiram (159 g ai/100 kg seed) used to control *Helminthosporium sativum* was efficient in the control of *P. oryzae*, often totally eliminating seed infection.

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Resumen

El añublo del trigo, causado por Pyricularia oryzae, *se identificó en 1985 en Brasil, en el norte de Paraná. La incidencia de la enfermedad fue esporádica en el primer año, pero, en el siguiente, se difundió en el norte y el oeste de Paraná, el noroeste de São Paulo y el sur de Mato Grosso do Sul. En 1988, la enfermedad fue observada también en Lagoa Vermelha y Passo Fundo en Rio Grande do Sul. En Paraná fue más grave en las fincas situadas a lo largo de los ríos Paranapanema, Tibagi, Ivaí y Piquiri. Las pérdidas fluctuaron entre insignificantes y totales. Se observó el mayor daño cuando se produjo la infección en el raquis, lo cual limitó el desarrollo de los granos y dio como resultado desde daños parciales hasta la muerte de la espiga por encima del punto de infección. Hasta el momento ninguna medida de control ha permitido un grado adecuado de reducción de la enfermedad, pero las investigaciones han mostrado que mancozeb + triciclazol, mancozeb + hidróxido de fentín y mancozeb + benzimidazol, cuando se aplican en forma preventiva (una o dos aspersiones) antes de las lluvias y durante el espigamiento, pueden reducir la infección de las espigas en un 50 a 70%.*

Effects of Soil and Foliar Treatments on Yields and Diseases of Wheat in Lowland Nepal

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Abstract

Studies were done at the National Wheat Development Program, Bhairahawa Farm, in the Tarai of Nepal to determine if yield was adversely affected by foliar blights and soilborne biotic factors. Data from 10 years of replicated trials showed a highly significant yield decline over time. The poster reports data for the years 1987-88 and 1898-90, which show that foliar blights and soilborne biotic factors are significantly decreasing yields.

Studies were done at the National Wheat Development Program, Bhairahawa Farm (105 masl, 27°6'N, 83°4'E), in the Tarai of Nepal to determine if yield was adversely affected by foliar blights and soilborne biotic factors. Data from 10 years of replicated trials have detected a highly significant yield decline over time.

Soil solarization and propiconazole were used as tools to study the effects of soilborne biotic factors and foliar blight pathogens, respectively. Data are reported for the years 1987-88 and 1989-90. In both years, there were significant positive effects of solarization and propiconazole on yield. Over both years, solarization increased yield by 12% and the use of propiconazole resulted in a 26% increase, the effects appearing additive. The data show that soilborne factors predispose the plants to foliar blight.

The principal foliar blight organism in 1987-88 was *Drechslera tritici-repentis*, however, in 1989-90 it was *Bipolaris sorokiniana*. Root rot estimation was done only in 1989-90. Reduction of root rot lesions by solarization was not statistically significant, although the trend was clear. Data from other experiments showed significant ($P<0.10$) reduction of root rots by various soil treatments.

Rice transplanted into the same plots of the wheat solarization experiments yielded significantly more ($P=0.05$) in the treated plots than the untreated. The average increase over 2 years was 16%. Thus, a residual effect of solarization was seen.

Soil solarization trials, without propiconazole sprays, in farmers' fields gave significant ($P=0.10$) increases in yield and significant ($P<0.10$) reductions of necrotic lesions on subcrown internodes and roots.

Isolations from roots and observations showed that *Fusarium* spp. predominated followed by *B. sorokiniana*. Other fungi observed on roots were *Periconia macrospinosa*, *Curvularia* sp., and *Pyrenochaeta* sp. In addition, pythium-like oospores were commonly observed in necrotic roots.

Nematode counts indicated high levels of *Hirschmanniella oryzae* in the soil. However, it was not found in wheat roots. Other common stylet bearing nematodes observed in soil were *Pratylenchus* sp. and *Tylenchorenchus* sp.

Future studies will further examine the losses caused by soilborne biotic factors and foliar blights, their etiology, and control.

Resumen

Se efectuaron estudios en el Programa Nacional de Desarrollo del Trigo, Finca Bhairahawa, en las tierras bajas de Nepal, para determinar si el rendimiento era afectado en forma negativa por los tizones foliares y factores bióticos desfavorables transmitidos por el suelo. Los datos obtenidos en 10 años de ensayos con repeticiones mostraron una reducción muy significativa del rendimiento en el transcurso del tiempo. Este trabajo comunica los datos correspondientes a los años 1987-1988 y 1989-1990, que indican que los tizones foliares y los factores bióticos desfavorables transmitidos por el suelo disminuyen considerablemente los rendimientos.

The Effect of Crop Rotation in Two Wheat Production Zones of Southeastern Ethiopia

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* Did not attend the conference.

Abstract

*A crop rotation experiment was conducted from 1984-89 at two research sites representative of wheat production zones on Andosols and Vertisols in southeastern Ethiopia. At each site, seven different 6-year rotations were used, comparing bread wheat (*Triticum aestivum *L. em Thell.) in monoculture with three rotations consisting of wheat grown 1 year out of 2 and with wheat grown 2 years out of 3. The break crops were faba bean (*Vicia faba*), rapeseed (*Brassica napus *L.) and an oat (*Avena sativum *L.) and vicia (*Vicia dasycarpa *Ten.) forage mixture. Noug (*Guizotia abyssinica*) was substituted for rapeseed on the Vertisol. Six different fertilizer levels were compared within each rotation.*

Analysis of wheat grain yield in 1989 indicated a highly significant effect of both rotation and fertilizer at both sites. On the Andosol, monoculture wheat yielded the lowest; first crop wheat after faba bean gave the largest yield increment relative to monoculture wheat (1366 kg/ha or +75.3%). Wheat in 2-year rotational systems outyielded second-crop wheat in the 3-year rotations by an average of 588 kg/ha (+25.9%); within each system, faba bean proved to be the most beneficial break crop. On the Vertisol, wheat in 2-year rotational systems outyielded second crop wheat in the 3-year rotations by an average of 1085 kg/ha (+78.6%), regardless of break crop. There was no response to phosphorus fertilizer at either site, but there was a highly significant linear response to nitrogen. Rotation by fertilizer interaction was not detected at either site. Treatment effects on other agronomic characters are also presented.

Materials and Methods

This experiment was conducted from 1984-89 at the Kulumsa and Robe research stations in the Arsi Region of Ethiopia on soils classified as a mollic Andosol and a pellic Vertisol, respectively. The two sites are warm temperate and humid, having a minimum mean monthly temperature during the growing season of 15.7 and 13.2°C, with 376 and 379 mm of rain falling from July to November, and are at an altitude of 2200 and 2420 masl, respectively.

The experiment was laid out in a split-plot design with rotational systems as main plots and fertilizer levels as subplots. The break crops used were faba bean (*Vicia faba*), rapeseed (*Brassica napus* L.), and an oat (*Avena sativum* L.) / vicia (*Vicia dasycarpa* Ten.) forage mixture. Noug (*Guizotia abyssinica*) was substituted for rapeseed on the Vertisol. In 1989 all plots were seeded with the bread wheat cultivar Enkoy, using a seed rate of 125 kg/ha. The fertilizer levels, expressed as kg N-P_2O_5/ha, were 0-0, 0-46, 9-23, 18-46, 27-46, and 36-46 on the Andosol and 0-0, 0-69, 14-35, 27-69, 41-69, and 55-69 on the Vertisol. Urea and TSP were used as the sources of N and P_2O_5, respectively.

Results and Discussion

Table 1 shows the effect of crop rotation on the 1989 grain yield of wheat on both soils. The wheat crops on the Vertisol yielded relatively lower. Single degree of freedom orthogonal contrasts were constructed to examine treatment effects.

For the Andosol, the appropriate contrast indicated that rotation treatments significantly (***) outyielded monoculture wheat, contributing 35.5% of the total sum of squares (SS) for rotation. Wheat yields from the 2-year rotational systems (2855 kg/ha) significantly (***) outyielded second-crop wheat in the 3-year rotations (2267 kg/ha), contributing an additional 38.4% of the rotation SS. Wheat yield significantly increased following the faba bean break crop of 1988 (**) and 1987 (*) relative to the other break crops, contributing a further 11.7 and 8.4% of the rotation SS, respectively. The maximum yield increase was 1366 kg/ha (75.3%), comparing wheat after faba bean in the 2-year rotation with monoculture wheat. Neither harvest index or thousand kernel weight (TKW) were affected by rotation. Grains/m^2 increased proportionally with treatment yield (r=0.959 ***), while hectoliter weight decreased (r=-0.535 ***). The results clearly indicate the benefit from the use of faba bean, in particular, in a 2-year rotational system for wheat production on this Andosol. Where the demand for cereal limits farmers to a 3-year rotation, faba bean would still be the preferred break crop.

On the Vertisol, the comparison of wheat in the 2-year rotational systems (2465 kg/ha) with second crop wheat in the 3-year rotations (1380 kg/ha) was significant (***) and contributed 78.6% of the total rotation SS. The only remaining significant (*) contrast was that comparing monoculture wheat with all six rotations, contributing 17.0% of the SS for rotation; presumably, much of this effect was due to the 2-year rotations. The contrasts among break crops in both the 2- and 3-year rotational systems were all nonsignificant. Harvest index (*), TKW (***), and grains/m^2 (*) all varied

Table 1. Grain yield of wheat as affected by crop rotation on an Andosol and a Vertisol in southeastern Ethiopia, 1989.

Treatment	Crop[a] rotation 1984	85	86	87	88	89	Andosol grain yield (kg/ha)	Vertisol grain yield (kg/ha)
1	Fb	W	O/V	W	*	W	2840 ab	2095 abc
2	O/V	W	*	W	Fb	W	3179 a	2686 a
3	*	W	Fb	W	O/V	W	2545 bc	2614 ab
4	Fb	W	W	O/V	W	W	2267 cd	1451 bc
5	O/V	W	W	*	W	W	1992 d	1292 c
6	*	W	W	Fb	W	W	2541 bc	1396 c
7	W	W	W	W	W	W	1813 d	1255 c
						Mean	2454	1827
						LSD (.01)	504	1164

[a] Crop: O/V = Oat/Vicia forage mixture; W = Wheat; Fb = Faba bean; * = Rapeseed on Andosol and noug on Vertisol.

Figures followed by the same letter are not significantly different at the 1% level of the LSD test.

significantly in response to rotation: all three characters were positively correlated with grain yield (r=0.477 ***, r=0.849 ***, and r=0.985 ***, respectively). Hectoliter weight was not affected by rotation. These results indicate the importance of a 2-year rotational system on this Vertisol, regardless of which of the three break crops is utilized.

On both soils, grain yield responded linearly (***) to added N, but there was no response to fertilizer P_2O_5. Comparing the highest fertilizer level to the control, grain yield increased by 808 kg/ha (38.3%) on the Andosol and 1616 kg/ha (142.9%) on the Vertisol, representing grain to nutrient ratios of 9.9 and 13.0, respectively. On the Andosol, grains/m^2 increased significantly (***), while hectoliter weight decreased (**) in response to fertilizer N; harvest index and TKW were unaffected. On the Vertisol, grains/m^2 (***), harvest index (*) and TKW (***) increased in response to N, while hectoliter weight decreased (***). Rotation by fertilizer interaction was nonsignificant for both soils for grain yield.

Table 2 lists the effects of treatments on other agronomic characteristics and soil parameters. For most characteristics, the effect of the faba bean break crop was similar to that of N fertilizer. Biomass yield exhibited the same response to rotation and fertilizer as grain yield.

Rotation significantly (*) increased the days to heading on the Andosol; monoculture wheat took 4.3 days longer to head compared to first-crop wheat after faba bean. Fertilizer N reduced days to heading on both soils by an average of 5.7 days relative to the check. Rotation did not affect days to maturity at either site. Fertilizer N reduced days to maturity on the Vertisol by up to 5.9 days at the highest N level.

Rotation affected plant height on the Andosol: the height of wheat after faba bean was increased by 14.2 cm relative to monoculture wheat. N fertilizer increased the height of wheat on both soils by an average of 26.2 cm.

Grain N content was affected by rotation on the Andosol and by fertilizer on both soils. The faba bean break also crop increased the N content of the wheat grain.

Neither crop rotation nor fertilizer level affected soil P, total soil N, and soil organic matter content on either soil. Soil pH was reduced relative to the control with the highest level of N by 0.15 unit on the Andosol and by 0.08 unit on the Vertisol. The failure to detect any effect of either rotation or fertilizer on total soil N, in particular, is surprising. Soil sampled from an adjacent long-term commercial seed field of Rhodes grass (*Chloris gayana* Kunth.) exhibited higher levels of both total N (0.288%) and organic matter (7.8%).

The density of most weed species increased in response to applied N, particularly on the Andosol. The most abundant N-responsive species on the Andosol with their densities at the highest levels of N and at 0 N (in brackets) follow:

- *Solanum nigrum*, 52.2 plants/m^2 (20.1*).
- *Galinsoga parviflora*, 17.6 (4.7 ***).
- *Amaranthus hybridus*, 15.9 (3.3 *).
- *Polygonum nepalense*, 10.1 (3.4 **).
- *Corrigiola littoralis*, 9.9 (2.3 **).

The density of two weed species varied (*) with rotation on the Vertisol: *Plantago minor* (24.5 plants/m^2 for monoculture

Table 2. Effect of crop rotation and fertilizer on agronomic characteristics of wheat and soil parameters on an Andosol and a Vertisol in southeastern Ethiopia, 1989.

	Characteristic		Andosol	Vertisol
1	Biomass yield	Rotation	**	*
		Fertilizer	***	***
		Mean (kg/ha)	8633	5937
2	Harvest index	Rotation	NS	*
		Fertilizer	NS	*
		Mean (%)	28.7	30.0
3	Days to heading	Rotation	*	NS
		Fertilizer	***	***
		Mean (days)	65.1	72.8
4	Grains/m²	Rotation	**	*
		Fertilizer	***	***
		Mean (no.)	9647	6364
5	Plant height	Rotation	**	NS
		Fertilizer	***	***
		Mean (cm)	85.5	74.0
6	Hectoliter weight	Rotation	**	NS
		Fertilizer	**	***
		Mean (kg/hl)	80.9	78.0
7	Thousand kernel weight	Rotation	NS	***
		Fertilizer	NS	***
		Mean (g)	25.3	27.4
8	N in grain	Rotation	*	NS
		Fertilizer	***	*
		Mean (%)	2.55	1.87
9	Soil P (Mehlich)	Rotation	NS	NS
		Fertilizer	NS	NS
		Mean (ppm)	28.7	20.1
10	Soil N (% total)	Rotation	NS	NS
		Fertilizer	NS	NS
		Mean (%)	0.215	0.253
11	Soil organic matter	Rotation	NS	NS
		Fertilizer	NS	NS
		Mean (%)	3.61	4.61
12	Soil pH	Rotation	NS	NS
		Fertilizer	**	*
		Mean (units)	6.31	5.87

*,**,*** = significant at the 0.05, 0.01, and 0.001 levels, respectively.

wheat versus 4.6 for the rotations) and *Phalaris paradoxa* (49.3 plants/m^2 following the noug break crops of 1988 and 1987 versus 18.3 plants/m^2 following the other break crops).

The severity of both leaf rust (*Puccinia recondita*) (***) and *Septoria tritici* (*) increased on wheat on the Vertisol site in response to N fertilizer, at least partially due to the more closed crop canopy. Other foliar pathogens were not affected by rotation.

The absence of a rotation by fertilizer interaction for all agronomic characters under examination could be attributed to the relatively low levels of N used in this study. This hypothesis is supported by the linearity of grain yield response to N in that rotation and fertilizer effects were additive.

Resumen

Entre 1984 y 1989, se efectuó un experimento de rotación de cultivos en dos sitios de estudio representativos de las zonas de producción de trigo en andosoles y vertisoles en el sudeste de Etiopía. En cada sitio se usaron siete rotaciones diferentes en seis años, para comparar el trigo harinero (Triticum aestivum L. em Thell.) *en monocultivo con tres rotaciones en las que se cultivó trigo en uno de dos años y en dos de tres años. Los otros cultivos incluidos fueron las habas* (Vicia faba), *la colza* (Brassica napus L.) *y una mezcla forrajera de avena* (Avena sativum L.) *y vicia* (Vicia dasycarpa Ten.). *El noug* (Guizotia aoyssinica) *sustituyó a la colza en el vertisol. Se compararon seis cantidades diferentes de fertilizante en cada rotación.*

Los análisis del rendimiento de grano del trigo efectuados en 1989 indicaron un efecto muy significativo tanto de la rotación como del fertilizante en ambos sitios. En el andosol, el monocultivo de trigo tuvo el rendimiento más bajo; el primer cultivo de trigo después de las habas mostró el aumento más grande del rendimiento en relación con el monocultivo de trigo (1,366 kg/ha o +75.3%). El trigo cultivado en sistemas de rotaciones de dos años superó el rendimiento del segundo cultivo de trigo en las rotaciones de tres años en un promedio de 588 kg/ha (+25.9%); en cada sistema, las habas resultaron el cultivo de rotación más provechoso. En el vertisol, el trigo en los sistemas de rotaciones de dos años superó el rendimiento del segundo cultivo de trigo en las rotaciones de tres años en un promedio de 1,085 kg/ha (+78.6%), cualquiera que fuera el cultivo de rotación. No hubo respuesta al fertilizante de fósforo en ninguno de los sitios, pero se observó una respuesta lineal muy siginificativa al nitrógeno. No se detectó una interacción entre la rotación y el fertilizante en ninguno de los dos sitios. También se presentan los efectos del tratamiento sobre otras características agronómicas.

Development of Aluminum-Tolerant Bread Wheat Varieties in Kenya

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Abstract

Acid soils (pH <5.0) and the associated toxicities of aluminum and manganese are critical problems in the major wheat growing areas of Kenya. Neutralizing the acidity through lime application may reduce Al toxicity. However, the high cost of transporting lime to the affected agricultural regions has restricted its general use. This has encouraged the development of bread wheat genotypes that can tolerate acidic soils. Over many years, some tolerant Kenyan wheat varieties have been indirectly developed through the benefits of multilocational testing. However, in recent years, Kenyan breeders have incorporated tolerance to soil acidity as a vital component of their breeding programs.

Introduction

Wheat has been grown in Kenya for more than 86 years. Currently, the country's total wheat production in a given year is approximately 210,000 t. All wheat in Kenya is rainfed at elevations between 1800 to 2900 meters above sea level (masl).

The three rusts (stem, leaf, and stripe) have been the greatest problems, although in recent years, partly due to moving wheat to nontraditional areas, some new constraints such as acidic soils with high amounts of soluble aluminum (Al) and manganese (Mn) have been encountered.

Soil Acidity in Kenya

The high Al and/or acid soils in Kenya are the Oxisols, Humic Ferrasols, and Latosols (FAO/UNESCO 1984). The Oxisols are highly weathered and leached soils and mostly red in color. The pH ranges from 4.8 to 5.3. In Kenya these soils mostly occur between 2100 and 3000 masl.

It is estimated that 46% (approximately 50,000 ha) of the wheat grown in the country has acid soil problems. Ssali and Nuwamanya (1981, 1982) indicated that there is a mosaic pattern of acidic soils in Kenya with various degrees of exchangeable Al. In the past, attempts have been made to ameliorate acidic soils using lime, but the high freight costs of lime and lack of equipment for its application have restricted its use. As a result, the use of tolerant varieties has become an attractive option.

Development of Varieties Tolerant to Acid Soils

The national wheat yield in Kenya is approximately 2.5 t/ha, but yields may be less than half this in areas where susceptible varieties are grown on acid soils. Foy et al. (1965, 1967) showed that differential tolerance to Al exists among wheat varieties. Most of the Al-tolerant genetic sources trace their origin from Brazil (Rajaram et al. 1981).

Breeding Methodology

The National Plant Breeding Research Centre (NPBRC), Njoro, is the only institution in Kenya that has a wheat breeding program. Apart from improving wheat varieties tolerant to acid soils, NPBRC must address other important

problems such as stripe rust, stem rust, septoria, and barley yellow dwarf virus. Research is conducted at Njoro and eight other sites that represent a wide range of agro-ecological zones.

Crosses are made between Kenyan wheats and introductions (mainly from CIMMYT, Madagascar, and Zambia) in combinations from simple and top crosses. A limited number of multiple and backcrosses are also made.

The F_2 generations are planted in soils with high acidity at Molo or Eldoret with the most vigorous single plants selected and bulked for planting F_3s. The F_3 generations are planted in Njoro where reselection for foliar diseases is made. Remaining generations are planted in Eldoret (acid soil area) and in Njoro. During this stage, further selection against foliar diseases is made and final selection of individual plants or bulk is done. Lines that do not show further segregation are entered in preliminary yield trials.

Introductions (approximately 1000 lines per year) are initially evaluated at Njoro to pre-select for foliar diseases. Lines that perform well in this respect are shuttled to acid soil regions where further selection is done to determine which lines are tolerant to acid soils. Only those lines that combine both disease resistance and acid soil tolerance are selected for further yield trials.

Results

Interestingly, in Kenya, wheat varieties (tolerant to acid soils) have never been selected specifically for Al/acid tolerance (Briggs and Nyachiro 1988). However, most of the varieties subsequently found tolerant to Al toxicity were selected from programs in which yield assessments would have been conducted on some acid soil sites (e.g., Molo and Eldoret), resulting in indirect selection for Al tolerance.

Some of the Kenyan-released varieties have been characterized further to determine their tolerance levels using hematoxylin staining techniques (Table 1). Independent results from Madagascar (Rakotondramanana, pers. comm.) confirm that varieties Romany, Kenya Tembo, and Kenya Tausi combine both good stem rust and Al/acid soil tolerance.

Table 2 shows some of the lines that scored very well on Al/acid soils and combined good stem rust and stripe rust resistance. Some commercial Kenyan wheat varieties (e.g., Kenya Kulungu, Mbuni, Kenya Tausi, and Kenya Popo) were included in the test for comparisons.

Generally, Al tolerance in Kenyan bread wheat cannot be traced to a single lineage, single ancestor, or to a set of closely related lines (Figure 1). However, those varieties that trace their ancestors to Romany (= Colotana 262/51 x Yaktana 54A), Ciano, Sonora 64, and Tobari 66 exhibit relatively high tolerance to acid soils. Examples of these varieties include, K. Tembo, K. Kongoni, K. Zabadi, K. Popo, K. Kulungu, K. Nungu, and K. Nyumbu among others. From this background information, it is apparent that genetic diversity for acid tolerance exists in Kenyan wheat varieties.

Anticipated Future Improvements and Gains in Breeding for Acid Soil Tolerance in Kenya

In recent years, Kenya's domestic consumption of wheat rose from 320,000 t in 1982-83 to 430,000 t in 1988-89. As the domestic production of wheat averages approximately 210,000 t annually, Kenya must import approximately 220,000 t

Table 1. Tolerance of some of the Kenyan bread wheat varieties to aluminum toxicity, results of hematoxylin staining test.

Origin	Category of tolerance[a]		
	Very tolerant (5)	Medium tolerant (3)	Susceptible (1)
Kenya	Romany[b] Kenya Tembo Kenya Kulungu Kenya Popo Kenya Swara[b] Kenya Kongoni Kenya Kima Kenya Tausi	Kenya Zabadi Kenya Nungu Paa[b]	Kenya Fahari Kenya Tumbili Bounty
CIMMYT	PF7748 (Previously known Maringá tolerant checks)		Siete Cerros (previously susceptible check)

[a] Tolerance based on hemotoxylin staining scores (Nyachiro 1986): 5 = tolerant and 1 = susceptible.
[b] Varieties Romany, Paa, and K. Swara are no longer recommended for commercial growing in Kenya due to high susceptibility to stripe rust.

Table 2. Some of the selections combining good stripe (YR) and stem (SR) rust resistance and acid soil tolerance, 1988-89 crop season in Njoro and Eldoret.

Variety or Cross	Njoro YR	Eldoret SR	Al/Acid Tolerance[a]
Kenya Kulungu	0	0	4
ALDAN'S'/PF70354 14/KTB'S'	20MS	0	4
IAS 54/ALD'S'	0	0	4
LOV23/BJY'S'/3/BB/NOR //CNO'S'/7C	0	0	4
MON'S'/ALD'S'	0	0	4
Mbuni = R357	10S	0	4
Kenya Tausi = K7156-1			
INDUS/NORTENO//K6648-2	40S	0	4
TI/TOB//ALD'S'/ ALD'S'/3/VEE'S'	20S	0	4
Kenya Popo	5S	0	4
IAS 58/MAD'S'//PEG'S'	0	0	4
R37/GHL121//KAL/BB/3/F12.71/COC	TR	0	4
YACO'S'/3/IAS63/ALD'S'//GTO/LV	10S	0	4
URES/F.3.71//TRM	0	0	4
SERI//MAYA/NAC	0	0	4

[a] Aluminum/acid soil tolerance was scored in Eldoret: 1 = Susceptible, 5 = Very tolerant.

(51% of total annual consumption) to satisfy the wheat demand. To develop Kenyan wheat production to the next yield level (more than 2.0-2.5 t/ha), the following are suggested as priority issues:

Develop a breeding program accompanied by aggressive research endeavors in agronomy and plant pathology.

- Establish an acid soil and aluminum stress screening laboratory in Kenya, which would help in pre-screening materials to reduce field testing costs.
- Establish a strong shuttle breeding program that will promote increased exchange of germplasm and complementary crossing blocks. That is to say, the best performing materials in Kenya may be sent to Brazil to be included in the crossing block to tap the good genes for acid soil tolerance. Some of the materials from past CIMMYT-Kenya shuttles have excellent performance in the Kenyan national program
- Establish training opportunities for Kenyan wheat researchers to visit Mexico (CIMMYT) and Brazil. In

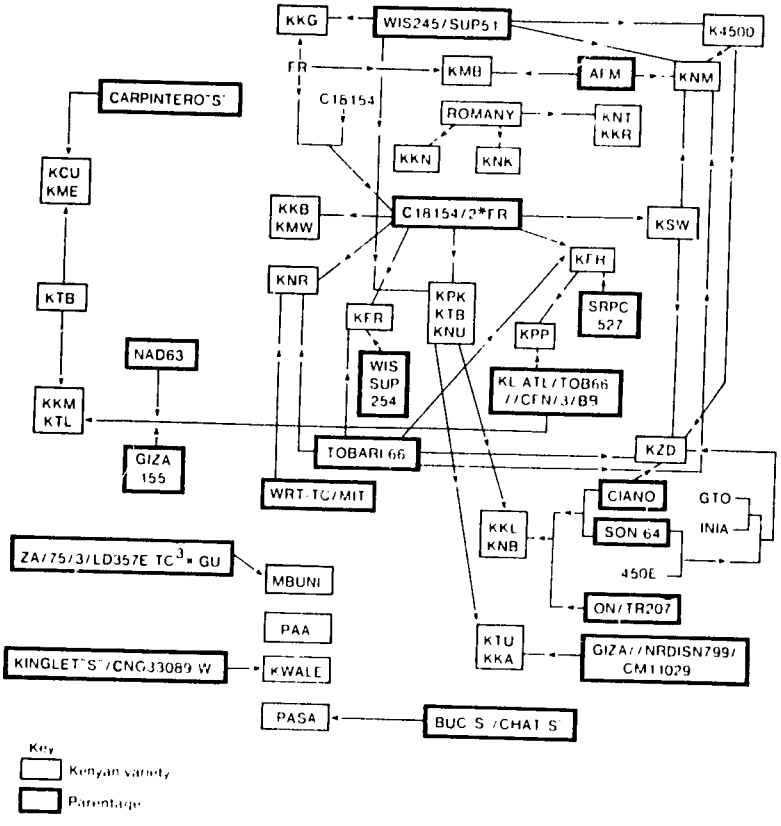

Figure 1. Summary of the parentage of some Kenyan varieties released up to 1989. Source: Briggs and Nyachiro, unpublished.

addition, Brazilian and CIMMYT researchers should visit Kenya to offer their expertise and to work with their Kenyan counterparts in the field.

Conclusion

Although wheat breeding progress in Kenya has been achieved, there is still potential for new and high yielding cultivars with more stable resistance to diseases and adaptation to acid soils. An important objective is to develop varieties with high yield potential and nutrient efficiencies, so that they can be grown in regions with soil limiting factors. The activities mentioned above on how research, and hence productivity, may be increased in problem soils may be costly to implement, but if implemented, results are bound to pay high dividends to the Kenyan wheat industry and collaborating countries.

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Resumen

Los suelos ácidos (pH < 5.0) y las concomitantes toxicidades por aluminio y manganeso son problemas críticos en las principales zonas productoras de trigo en Kenya. La neutralización de la acidez mediante la aplicación de cal puede reducir la toxicidad por el aluminio. No obstante, el alto costo de transportar la cal a las regiones agrícolas afectadas ha restringido el empleo generalizado. Esto ha fomentado la generación de genotipos de trigo harinero que puedan tolerar los suelos ácidos. Durante muchos años, se han desarrollado en forma indirecta algunas variedades tolerantes de trigo en Kenya, gracias a los beneficios de los ensayos en múltiples localidades. Sin embargo, en los últimos años los fitomejoradores de Kenya han incorporado la tolerancia a la acidez del suelo como un componente vital de sus programas de mejoramiento.

Influence of the Chemical Forms of Phytotoxic Aluminum on the Uptake of Aluminum by Wheat Roots

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Abstract

Aluminum (Al) toxicity studies generally refer to the total concentration of Al in soils and nutrient solutions, which does not provide information on the chemical forms of the phytotoxic Al present. Such information is essential for estimating the extent to which Al may be absorbed by roots. Aluminum may form complexes with several soluble anions such as OH^-, PO_4^{3-}, SO_4^{2-}, and organic ligands, which decrease the concentration of free Al (Al^{3+}) in solution. The objective of this poster is to evaluate the uptake of Al by wheat roots as a function of the Al chemical forms in solution to aid in interpreting results from Al toxicity experiments and to help plant breeders to select for aluminum tolerance among wheat varieties. The ionic strength experiment demonstrated that Al toxicity effects on cultivars Anahuac, IAC 5-Maringá, and IAPAR 6-Tapejara were better correlated with the activity of Al^{3+} rather than with the concentration of total soluble Al, $Al(OH)_2^+$, $AlOH^{2+}$, KCL-exchangeable Al, or percentage of Al saturation.

The wheat growing areas in Brazil are located mainly in regions having acid soils where aluminum toxicity may limit plant growth. Olmos and Camargo (1976) reported that soils in these regions contain Al in soil solution in amounts high enough to restrict a deep and vigorous root system and hence, in addition to Al toxicity, plants may be drought stressed. The chemical forms of the Al may be an important factor that influences Al availability. Recent observations suggest that wheat cultivars are primarily responsive to the activity of free Al^{3+} in solution; consequently, it appears that there is a need to consider Al's various chemical forms when assessing Al availability to plants.

Determining the chemical forms of phytotoxic Al in order to predict Al toxicity in both soils and nutrient solutions has been a serious problem. Soluble anions such as hydroxide, phosphate, sulfate, and several organic ligands may create a complex polymer or precipitate Al, which would considerably decrease the phytotoxic fraction remaining in the solution. Thus, total Al does not necessarily reflect phytotoxic Al in solution when these anions are present.

Some modifications have been made in colorimetric techniques for the determination of Al in order to measure fractions that are predominantly phytotoxic. Measurements of Al in nutrient solution by the aluminum colorimetric technique without acidification and heating (called monomeric Al) did correlate well with plant response under various P:Al and OH:Al ratios. However, this technique failed to predict phytotoxic Al in solutions with widely varying SO_4^{2-} concentrations.

James et al. (1983) measured Al concentration in solutions by the 8-hydroxyquinoline method with 15 seconds of reaction time. They termed this fraction labile Al, which closely corresponded to the sum of the predicted concentrations of Al^{3+} and $AlOH^{2+}$ in a simple Al-OH system.

In addition to the above studies, we have also used analytical techniques with the computer program called GEOCHEM (Sposito and Mattigod 1980), which was also used to calculate the various Al forms in soil and nutrient solutions (Pavan and Bingham 1982, Pavan et al. 1982).

Greenhouse experiments were conducted using nutrient solutions and acid soils collected from the wheat growing areas of the State of Paraná. The soils are kaolinitic, acidic, low in exchangeable bases, and relatively high in KCl-exchangeable Al.

Seed of *Triticum aestivum* L. em. Thell. cultivars Anahuac, IAC 5-Maringá, and IAPAR 6-Tapejara were germinated in moist paper towels and transferred to plastic pots containing acid soils or diluted nutrient solutions (Pavan and Bingham 1982). After harvesting, approximately 0.5 kg of soil was collected from each pot, air dried, and prepared for saturation extract analysis. The soil extracts and nutrient solutions were analyzed for pH, electrical conductivity (EC), Al, Ca, Mg, K, Na, SO_4, Cl, P, and NO_3 and trace metals Cu, Fe, Mn, and Zn. These data were transformed into the appropriate input units for GEOCHEM to characterize the saturation extract with respect to ionic strength, the molar concentration of each of the Al-containing complexes, and the molar concentration of free ionic Al (Al^{3+}). The activity of Al^{3+} was computed from the value of Al^{3+} and the activity coefficient calculated with the Davies equation (Davies 1962).

For Al, the principle chemical forms considered were Al^{3+}, the free ion, and complexes with OH^-, PO_4^{3+}, SO_4^{2-}, NO_3, and Cl^-.

Figure 1 shows the relationship between root growth as a function of the concentration of total soluble Al (Al_t) and Al^{3+} and the activity of Al^{3+}. These results reveal a wide range of root growth values for each concentration of the nutrient solution (ionic strength effect). However, plotting root growth in relation to the

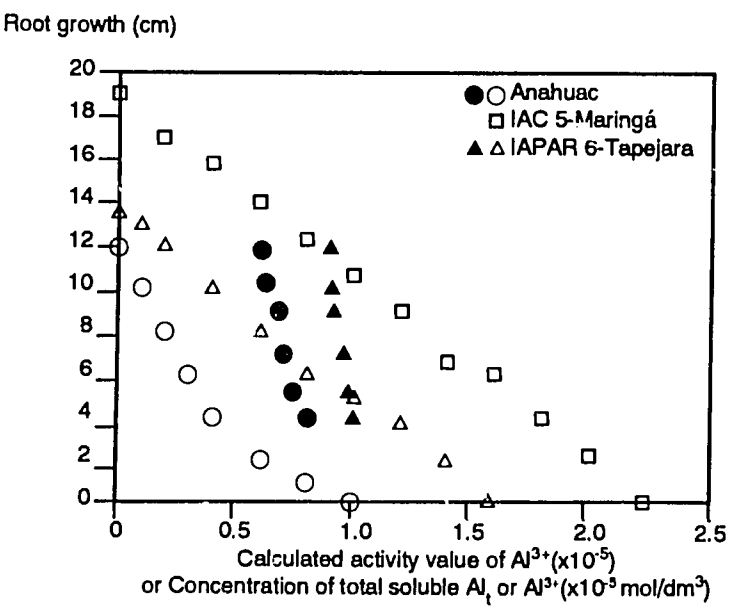

Figure 1. Wheat root growth of three cultivars in relation to activity value of Al^{3+} (open circles, triangles, and squares) and the concentration of Al_t (black triangles) and Al^{3+} (black circles).

GEOCHEM-calculated activity value for Al^{3+} produced a more continuous function. Table 1 shows the correlation coefficient for wheat root growth vs. $AlSO_4^+$, $AlOH^{2+}$, $Al(OH)_2^+$, and Al_t activity values. The highest correlations for Anahuac, IAC 5, and IAPAR 6 were obtained with the Al^{3+} activity value. Anahuac was much more sensitive to Al than IAC 5 and IAPAR 6. These results agree with earlier findings of Camargo and Oliveira (1981).

Table 1. Correlation coefficient for Anahuac, IAC 5, and IAPAR 6 wheat root growth vs. $AlOH^{2+}$, $Al(OH)_2^+$, Al^{3+}, and $AlSO_4^+$ activity values.

	Correlation coefficient		
Al parameter	Anahuac	IAC 5	IAPAR 6
$Al(OH)_2^+$	0.43NS	0.44NS	0.40NS
$AlOH^{2+}$	0.92***	0.90***	0.89***
Al^{3+}	0.99***	0.98***	0.98***
$AlSO_4^+$	0.34NS	0.40NS	0.36NS

*** indicates statistical significance at the 0.001 level; NS = nonsignificant.

In order to evaluate the various soil Al parameters in terms of plant response, wheat root growth was plotted against several parameters, e.g., percent Al saturation, concentration of Al, concentration of Al^{3+}, and activity of Al^{3+}. The reduction in wheat root growth correlated best with the activity of Al^{3+} rather than with percent Al saturation, concentration of Al_t or Al^{3+}. The Al^{3+} activity values for the soil solutions compared favorably with the critical Al^{3+} activity data observed in the nutrient solutions. For soil solutions, the correlation coefficients between root growth and the various Al parameters were as follows: percent Al saturation, -0.84; Al_t, -0.86; Al^{3+}, -0.93; and activity of Al^{3+}, -0.99.

Figure 2 shows the relationship between the Al concentration in wheat leaves and the activity of Al^{3+} in soil and in nutrient

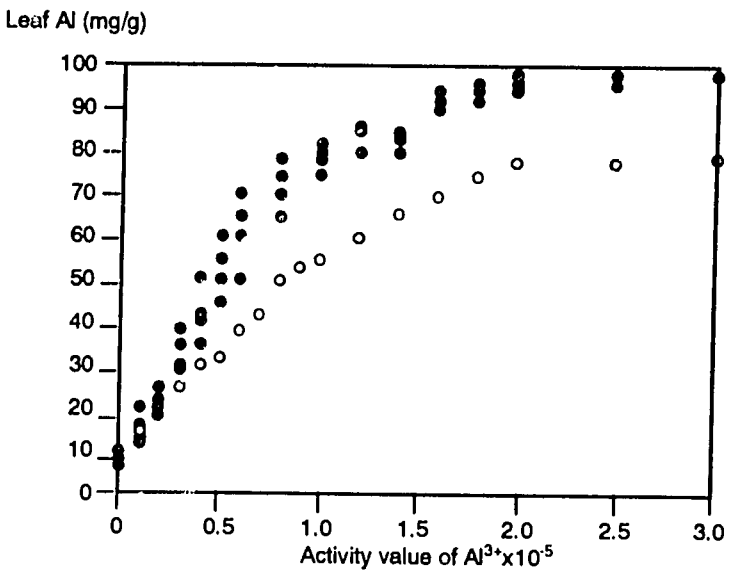

Figure 2. Concentration of Al in wheat leaves in relation to the activity value of Al^{3+} in soil solutions (black circles) and nutrient solutions (open circles).

solution. The Al^{3+} activity and leaf-Al produced a continuous function, with Al uptake by roots corresponding to increases in Al^{3+} activity.

Results from these experiments contribute further to an understanding of Al availability, uptake, and accumulation in wheat cultivars.

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Resumen

Los estudios sobre la toxicidad del aluminio (Al) generalmente se refieren a la concentración total de Al en la solución de nutrimentos o del suelo y no proporcionan información sobre las formas químicas fitotóxicas presentes. Esta información es esencial para estimar el grado en que el Al puede ser absorbido por las raíces. El aluminio puede formar complejos con varios aniones solubles, como OH^-, PO_4^{3-}, SO_4^{2-}, y ligandos orgánicos, que disminuyen la concentración de aluminio libre (Al^{3+}) en solución. El propósito de este trabajo es evaluar la absorción de Al por las raíces de trigo como función de las formas químicas de Al en solución, para contribuir a interpretar los resultados de los experimentos sobre la toxicidad del aluminio y ayudar a los fitomejoradores a seleccionar para obtener tolerancia al mineral. El experimento sobre la fuerza iónica demostró que los efectos de la toxicidad por el aluminio en las variedades Anahuac, IAC 5-Maringá e IAPAR 6-Tapejara correspondían con la actividad del Al^{3+}, más que con la concentración de Al, $Al(OH)_2^+$, $AlOH^{2+}$ y Al intercambiable con KCl totales solubles, y el porcentaje de saturación por Al.

Assessment of Grain Set Failure and Diagnosis for Boron Deficiency in Wheat

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Abstract

This poster presents some information on the assessment of grain set failure and diagnosis of boron (B) deficiency in wheat. Basal floret fertility (average number of grains in the two basal florets, F1+F2, of 10 central spikelets) is proposed as an index for assessment of grain set failure. The index correlated well with overall floret fertility (% fully developed florets with grain, R^2 = 0.95) and spikelet fertility (number of grains / spikelet relative to the maximum, R^2 = 0.91) in several wheat genotypes grown in the field and sand culture. The maximum number of 1.9-2.0 grains / F1+F2, constant over genotypes and conditions, is a built in reference that allows the index to be used in farmers' fields and other situations in the absence of a no-sterility control.

The reduction or elimination of grain set failure by B application has been the basis for diagnosis of B deficiency as the cause of sterility in Brazil, China, Thailand, and Nepal. Soil and plant tissue analyses are additional diagnostic tools, but there are some difficulties with both for B deficiency in wheat. Soil analyses for available B gave varying results, with sterility observed in soil with 0.18 to 0.52 mg B / kg in China and less than 0.15 mg B / kg in Thailand. The reduction in the number of grains / spikelet by B deficiency in a soil with a given level of hot water soluble B varied with wheat genotypes and sowing dates. Well defined relationships between leaf B concentrations and grain set failure were found for SW41 and other wheat genotypes sensitive to B deficiency; more tolerant genotypes did not fit into the same relationships. B concentration in the developing ears at boot stage was more closely related to grain set, without genotypic variations.

An Assessment of Grain Set Failure in Wheat

Floret infertility or grain set failure has been frequently observed in wheat growing areas of Heilongjiang Province (Li et al. 1978) and the western part of Yunan Province of China (C.E. Mann, pers. comm.), the Central West Region of Brazil (da Silva and de Andrade 1983, da Silva, pers. comm.), northern Thailand (Rerkasem et al. 1989, J.G. Connell and C.E. Mann, pers. comm., and Rerkasem, unpub.), the eastern Tarai and other parts of Nepal (Sthapit 1988, B.R. Sthapit and P.R. Hobbs, pers. comm.), and throughout Bangladesh (D.A. Saunders, pers. comm.). In these cases, in which grain set may fail in any floret from the basal (F1, Kirby and Appleyard 1987) upward, the florets appear complete with fully developed palea and lemma, but the anthers are absent or poorly developed, with few and malformed pollen grains. The florets may remain open for several days at anthesis, giving the ear a transparent appearance against the sun.

This type of sterility should not be confused with the incomplete, also termed sterile, florets (Bonnett 1966) commonly found at the tip of each spikelet. In practice, the distinction is often far from obvious. To overcome this difficulty, it is proposed that grain set failure be assessed by an index of basal floret fertility, which is the average number of grains set in the two basal florets (F1+F2) of 10 central spikelets of the wheat ears (R.A. Fischer, pers. comm.).

From a field experiment on B deficiency involving four wheat genotypes, the index correlated well with floret fertility of the whole ear (% fully developed florets in the whole ear with grain, $R^2 = 0.95$) and spikelet fertility (number of grains/spikelet as % of the maximum in each genotype obtained with sufficient B; $R^2 = 0.91$). The correlations are shown for genotype SW41 between basal florets fertility with overall floret fertility (Figure 1a) and with number of grains/spikelet (Figure 1b). Similar correlations were

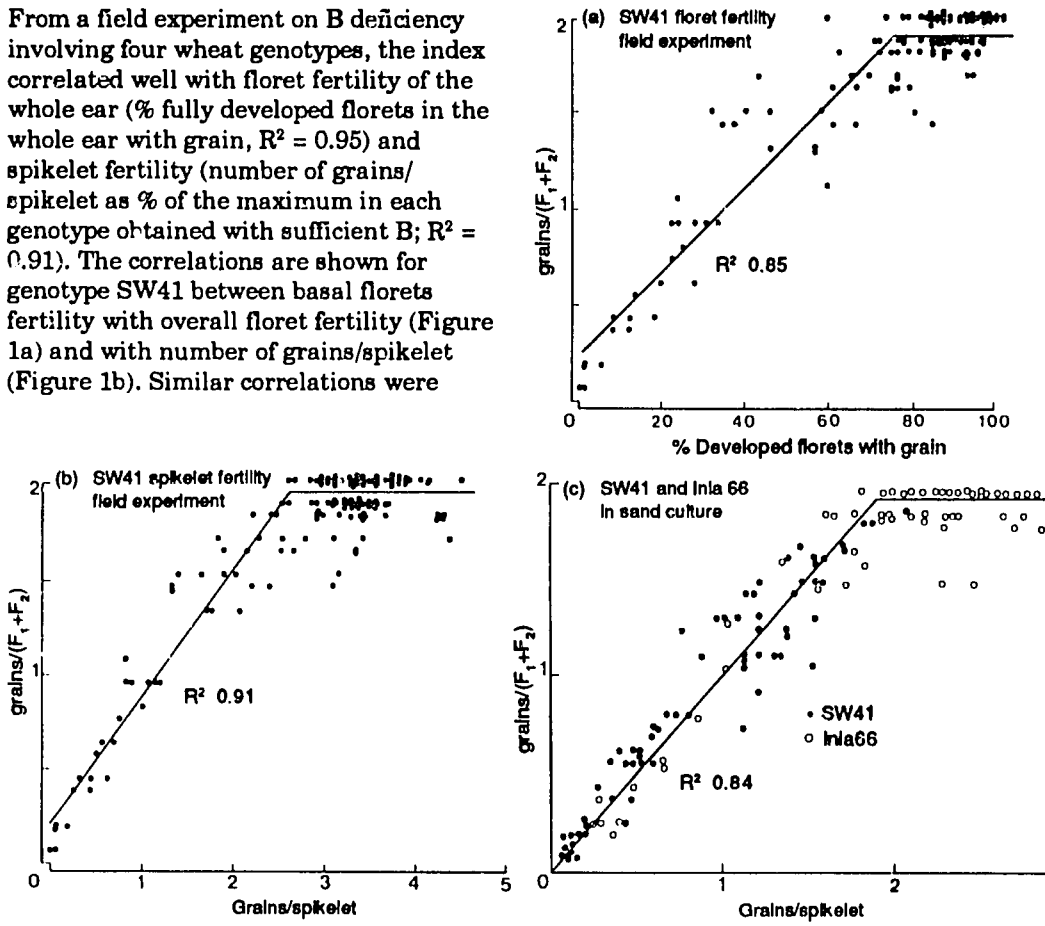

Figure 1. Relationships between basal floret fertility and (a) overall floret fertility, (b) spikelet fetility of SW41 wheat grown in the field, and (c) spikelet fertility of SW41 (•) and Inia 66 (o) grown in a sand culture. Each point represents one ear.

Table 1. Effects of soil B levels and sowing date on the number of grains/spikelet in SW23 wheat.

Soil B level	1987 HWSB[a] (mg B/kg)	1987 Oct. 16 (grains/spikelet)	1987 Nov. 16 (grains/spikelet)	1988 HWSB (mg B/kg)	1988 Nov. 10 (grains/spikelet)	1988 Dec. 19 (grains/spikelet)
B1	0.08	2.14a	1.22a	nd	1.50a	2.03a
B2	0.17	2.74b	2.15b	0.14	2.26b	2.42b
B3	0.53	2.80b	2.09b	nd	3.26c	2.75b

[a] HWSB = Hot water soluble boron.
Numbers in same column followed by same letter not significantly different ($p<.05$).
In 1988, B1 = B2 plus 2500 kg lime/ha; B3 = B2 plus 10 kg borax/ha.

observed between the basal floret fertility and spikelet fertility in wheats grown in sand cultures (Figure 1c). The maximum number of 1.9-2.0 grains/F1+F2, constant over genotypes and conditions, is a built-in reference that allows the index to be used in farmers' fields and other situations in the absence of a no-sterility control.

Diagnosis of Boron Deficiency

The reduction or elimination of grain set failure in wheat in China (Li et al. 1978), Brazil (da Silva and de Andrade 1983), Thailand (Rerkasem et al. 1989) and Nepal (Sthapit 1988) by B application established B deficiency as the cause of the problem in these locations. Soil and tissue analyses are additional diagnostic tools, but there are some difficulties with B deficiency in wheat. In China, sterility was found on soils with available B levels from 0.18 to 0.52 mg B/kg (method of analysis unspecified, Li et al. 1978). In Thailand, grain set was reduced in soils with less than 0.15 mg hot water soluble B/kg (Rerkasem et al. 1989), with different responses among genotypes (Rerkasem and Jamjod 1989), and sowing times (Table 1) in the same soil. Well defined relationships between leaf B concentrations and grain set failure were found for SW41 and other wheat genotypes sensitive to B deficiency, but more tolerant genotypes did not fit the same relationships (Figure 2).

Boron concentration in the developing ears in the boot (Feekes' Scale 10) is more closely related to grain set without the genotypic variations (Table 2).

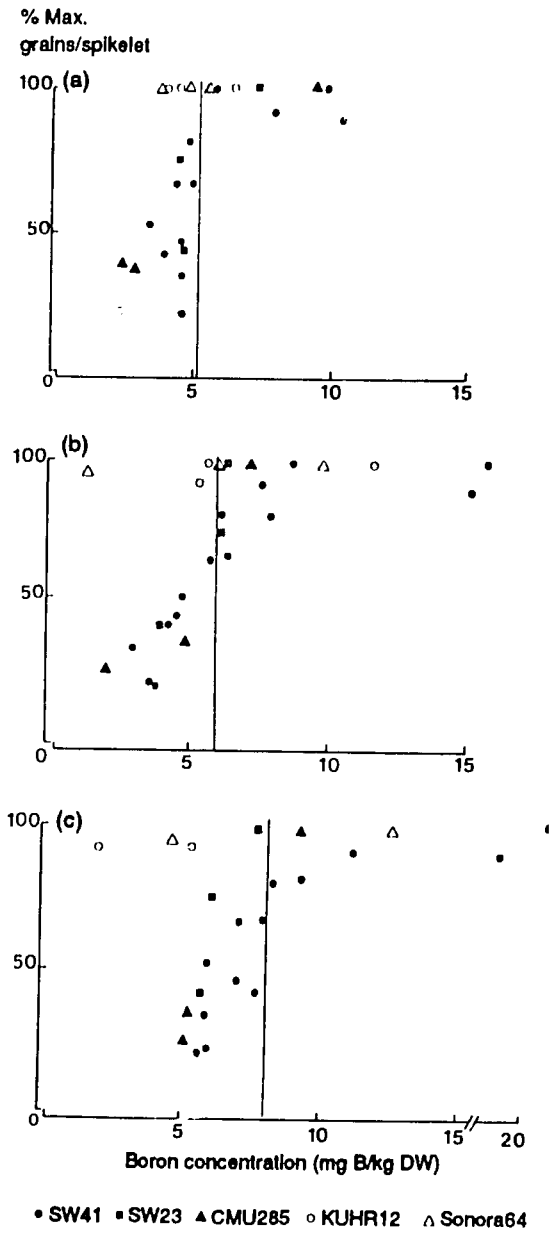

Figure 2. Relationships between grain set (number of grains/spikelet as % maximum) and boron concentrations in (a) youngest emerged blade (YEB) at Feekes' 8.5, (b) YEB at Feekes' 5, and (c) whole tops at Feekes' 5. Vertical line separates SW41 responsive and nonresponsive actions to increasing boron concentrations (Cate and Nelson 1971). Each point represents four replicates.

Table 2. Effects of soil B levels and genotype on B concentration of developing wheat ears at booting stage (Feekes' 10) and the average number of grains/(F1+F2) of central spikelets.

Boron treatment[a]	Genotype	[B] Ear (mg B/kg) (F1+F2)	Number of grains/
B0 (0.10 mg HWSB/kg)	SW 41	4.1	0.81
	SW 23	4.7	1.55
	Inia 66	5.0	1.76
	Sonora 64	5.7	1.98
B1 (0.16 mg HWSB/kg)	SW 41	4.4	1.76
	SW 23	4.9	1.97
	Inia 66	5.5	1.98
	Sonora 64	5.5	1.98
B2 (0.29 mg HWSB/kg)	SW 41	7.2	1.91
	SW 23	6.7	1.93
	Inia 66	5.5	1.98
	Sonora 64	7.4	1.98
B3 (0.33 mg HWSB/kg)	SW 41	7.3	1.88
	SW 23	7.9	1.97
	Inia 66	5.9	1.98
	Sonora 64	6.9	1.98
LSD (p<.05)		1.0	0.08
B x Genotype effects significant at p<		.001	.001

[a] Created by borax applications at various rates in previous years; average soil B levels at sowing in parentheses.

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Resumen

Este trabajo presenta información sobre la evaluación de la no formación de grano y el diagnóstico de la carencia de boro (B) en el trigo. Se propone la fertilidad de las florecillas basales (cantidad media de granos en las dos florecillas basales, F1 + F2, de 10 espiguillas centrales) como índice para evaluar la no formación de grano. El índice coincidió bien con la fertilidad general de las florecillas (% de florecillas totalmente desarrolladas con grano, R^2 = 0.95) y la fertilidad de las espiguillas (número de granos / espiguilla en relación con el máximo, R^2 = 0.91) en varios genotipos de trigo producidos en el campo y en cultivo con arena. La cantidad máxima de 1.9-2.0 granos / F1 + F2, constante en todos los genotipos y condiciones, es una referencia intrínseca que permite usar el índice en los campos de los agricultores y otras situaciones cuando no existe un control de la no esterilidad.

La reducción o solución de la no formación de grano mediante la aplicación de boro ha sido la base para el diagnóstico de carencia de B como causa de la esterilidad en Brasil, China, Tailandia y Nepal. Los análisis del suelo y de tejidos vegetales son instrumentos adicionales de diagnóstico, pero ambos presentan dificultades para aplicarlos a la carencia de B en el trigo. Los análisis del suelo para determinar el B disponible dieron resultados variables; se observó esterilidad en suelos con 0.18 a 0.52 mg de B / kg en China y con menos de 0.15 mg de B / kg en Tailandia. La reducción de la cantidad de granos / espiguilla causada por la deficiencia de B en un suelo con una determinada cantidad de B soluble en agua caliente varió según los genotipos de trigo y las fechas de siembra. Se encontraron relaciones bien definidas entre las concentraciones foliares de B y la no formación de grano en SW41 y otros genotipos de trigo sensibles a la carencia de B; los genotipos más tolerantes no presentaron las mismas relaciones. La concentración de B en las espigas en desarrollo durante la etapa del embuchamiento se relacionó más estrechamente con la producción de grano, sin variaciones genotípicas.

Response of Wheat (*Triticum aestivum*) to Soil Compaction

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Abstract

*Excessive soil preparation provokes degradation of the soil structure and the formation of compacted layers, with resulting reductions in root penetration and crop productivity. The objective of this research was to study the effect of soil compaction on root development, dry matter production, and grain yield of wheat (*Triticum aestivum *cv. OCEPAR 7-Batuira) under field conditions. Root length, dry matter production, and grain yield were all reduced by soil compaction. Root development was satisfactory up to a soil bulk density of 1.40 g/cm^3, above which root penetration was reduced.*

Introduction

In mechanized agriculture, the soil is subjected not only to the multiple effects of soil preparation implements, but also to the passage of agricultural vehicles, all of which affect soil structure. Soil compaction is the principal effect observed.

In clay soils, the reduction in root penetration, which occurs following excessive soil preparation has been attributed to direct effects of subsurface compacted layers (Kemper and Derpsch 1981, Cintra and Mielniczuk 1983), and to nutrient imbalances, including aluminum, manganese, and iron toxicity (Foy 1975, Malavolta et al. 1977).

Although it is of interest to determine the critical soil density for root growth, often it is the depth of the compacted layer that is more important in determining root development. In the studies of Bacchi (1976), when the compacted layer was below 10 cm, roots were restricted to the surface layer, as root diameter was greater than pore size in the compacted layer, making root penetration difficult. However, when the compaction was superficial (above 10 cm), root growth and penetration of the compacted layer started soon after germination when the roots were still fine enough to permit their penetration and growth through the small pores.

Soil compaction, apart from its direct effect on root growth, has indirect effects on crop yield, although results are inconsistent. In some studies, soil compaction has led to yield reductions, while in other studies yields have increased.

The principal objective of this study was to evaluate the direct effects of soil compaction on root growth and the indirect effects on wheat yield.

Materials and Methods

The experiment was carried out at the Palotina Experiment Station (Centro de Pesquisa, Palotina) of the Organization of Paraná State Cooperatives (OCEPAR), Brazil. The soil is a eutrophic "Latossolo roxo" (Oxisol) clay, with a mean of 82% clay, 12% silt, and 6% sand, and with 1.92% organic matter.

The following combinations of soil preparation implements were used to provide five treatments whose basic differences were in the degree, depth, and thickness of the compacted layer:

- T1 = Direct seeding (no-till) in both summer and winter.
- T2 = Preparation with disks in summer and direct seeding in winter.
- T3 = Moldboard plow in both summer and winter.
- T4 = Chisel plow in summer, moldboard plow in winter.
- T5 = Moldboard plow in summer, direct seeding in winter.

The experimental design was randomized blocks with three replications. OCEPAR 7-Batuira was the wheat cultivar used.

Soil compaction curves (Stof et al. 1983) and grain yield were evaluated in the 1989 wheat crop season, whereas all other data, such as bulk density, root lengths (using the method of Bohn 1979), and dry matter production were taken 30 days after emergence of the wheat crop during the 1990 season.

Results and Discussion

The effects of the treatments on soil bulk density are presented in Table 1; curves of resistance to an impact penetrometer are shown in Figure 1. The direct and indirect effects of this compaction on root distribution and length, dry matter production at 30 days, and grain yield are shown in Tables 2 and 3. These results show that wheat crop productivity can be markedly reduced by soil compaction.

Table 1. Soil bulk density in five treatments with different tillage systems.

Soil depth (cm)	Treatment T1	T2	T3	T4	T5
			g/cm³		
2-10	1.47	1.40	1.37	1.34	1.40
10-18	1.58	1.56	1.38	1.38	1.36
18-25	1.48	1.49	1.39	1.37	1.39
25-33	1.47	1.41	1.38	1.35	1.36
33-40	1.42	1.35	1.36	1.36	1.39

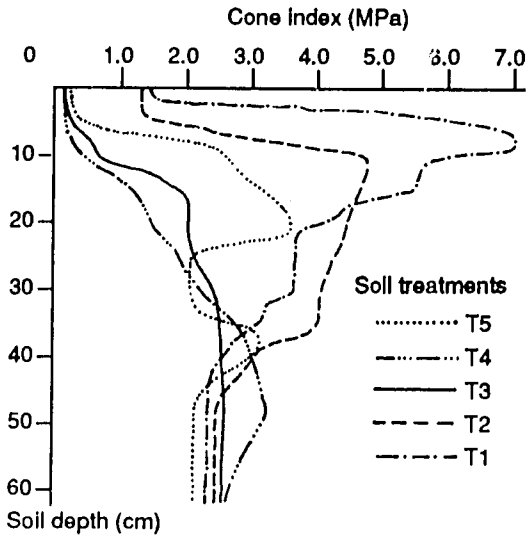

Figure 1. Impact penetrometer resistance curves of five soil preparation treatments. OCEPAR, Palontina, 1990. MPa = mega-Pascals.

Compaction is characterized by an increase in soil bulk density and a decrease in pore space as a result of the effect of agricultural activities on soil structural stability. The data shown in Table 1 and Figure 1 are evidence of the compaction in the treatments by the action of agricultural implements. It is worthy of note that some of the treatments, especially T1 and T2, are commonly used by farmers in the western part of Paraná.

The presence of compaction resulted in a large proportion of the roots of the wheat crop accumulating above the compacted layer where the soil physical and chemical conditions were more adequate. Treatments T1 and T2 had more roots in the top 10 cm than the other treatments

with 64 and 55%, respectively, of their roots concentrated above the compacted layer. In the other treatments, a better root distribution was observed in the profile.

Based on the means of the bulk density data, it appears that root growth continued relatively unaffected up to soil bulk densities of 1.40 g/cm³. At higher bulk densities, a reduction in the ability of roots to penetrate the compacted layer was observed and, as a result, most roots were confined to the surface layer above the compaction.

It appears that the more superficial soil compaction of T1 and T2 had a greater effect on the early growth of the wheat crop than did a deeper compacted layer, apparently in agreement with the results of Bacchi (1976), who found that a deeper compacted layer, even if thicker, was not as detrimental to root growth as a superficial layer. When the compacted layer was deeper in this study, root penetration, shoot dry matter at 30 days, and grain yield were not affected significantly, probably because of the greater soil volume explored by the roots.

Table 2. Quantity (%) of wheat roots at different soil depths in five treatments with different tillage systems.

Soil depth (cm)	Treatment T1	T2	T3	T4	T5
			%		
0-5	44	21	24	20	28
6-10	20	35	13	17	25
11-15	10	12	15	15	11
16-20	7	9	13	14	11
21-25	7	7	12	12	8
26-30	5	6	10	8	8
31-35	5	5	7	8	7
36-40	2	5	6	6	6

Table 3. Root length, above ground dry matter, and grain yield of wheat in five treatments with different tillage systems.

Treatment	Root length[a] (cm/80 cm³)	%	Shoot dry matter[a] (g/0.25 m²)	%	Grain yield[b] (kg/ha)	%
T1	19.7	63	43.5	67	2262	70
T2	23.5	75	43.2	67	2508	78
T3	31.5	100	59.2	92	3099	97
T4	27.8	88	64.5	100	3186	100
T5	24.5	78	55.3	86	2636	82

[a] 30 days after germination.
[b] Grain yield in 1989.

The compaction process causes several modifications in the soil which may influence root penetration. Apart from the mechanical resistance, there is possible oxygen deficiency and the formation of a reducing (anaerobic) environment due to saturation of the layer after rainfall. This, in turn, increases the availability of manganese, causing manganese toxicity resulting in reduced root penetration, even in limed soils with an adequate pH.

When the root lengths observed in the samples from the eight soil depths were summed to give a measure of relative root growth (Table 3), reductions were evident in the root growth in treatments T1 and T2, coinciding with the reductions in early dry matter production and grain yield.

The effects of compaction on crop yields is due to the reduced depth and volume of soil explored by the roots, with a resulting reduction in capacity to absorb water and nutrients, as well as an air-filled pore space in the compacted layer below the minimum necessary for root growth (Rosenber 1964, Taylor 1971, Cintra and Mielnizuck 1983).

Dry matter weights 30 days after emergence and grain yields of treatments T1 and T2 were approximately 30% lower than those of treatments T3 and T4 (Table 3), a difference that was probably due to the greater compaction and reduced root growth in the former treatments.

The presence of compacted layers, whether they be superficial or deeper, restrict root penetration, and consequently, reduce the soil volume explored and the uptake of water and nutrients. In crop years with sufficient, well-distributed, rainfall, yield reductions due to compaction have not been shown. However, in abnormal years with prolonged dry spells, the crop suffers drought stress in compacted fields and yields are reduced.

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Resumen

*La preparación excesiva del suelo provoca la degradación de la estructura de éste y la formación de capas compactas, con la resultante reducción de la penetración de las raíces y la productividad del cultivo. El propósito de esta investigación fue estudiar el efecto del apisonamiento del suelo sobre el desarrollo radical, la producción de materia seca y el rendimiento de grano en el trigo (*Triticum aestivum *cv. OCEPAR 7-Batuira) en condiciones de campo. El apisonamiento del suelo redujo la longitud de las raíces, la producción de materia seca y el rendimiento de grano. El desarrollo radical fue satisfactorio hasta una densidad aparente del suelo de 1.40 g/cm^3, por encima de la cual se redujo la penetración de las raíces.*

Rooting Depth, Growth Cycle Duration, and Timing of the Jointing Stage in Wheat: Traits that Can Contribute to Early Drought Tolerance

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Abstract

The effects of early drought during the tillering and early jointing stages on the rooting patterns, water extraction profiles, and yield of three bread wheat cultivars were examined. The cultivars, which had different growth cycle durations (two intermediate, one short) and jointing times, were grown in mini-drainage lysimeters, some of which were equipped with time-domain reflectometry probes. The two intermediate-cycle wheats had deeper roots and thus extracted more water from further down in the soil profile. Drought reduced yield in all cultivars, but the genotype that combined late initiation of jointing with deep rooting was affected the least. Late initiation of jointing or deep rooting, alone, did not reduce the effects of drought.

Introduction

Wheat grown in the northern and western areas of the Argentine Pampas is often exposed to drought during early growth stages, i.e., tillering and sometimes jointing. Yield variability across years is strongly associated with the intensity of these droughts (C.R. Rebella and R. Díaz, unpublished).

Field experiments (G.O. Magrin, S.G. Meira, and E. Guevara, unpublished) suggest that intermediate-cycle wheats can extract more water than short-cycle cultivars and that the time the jointing stage occurs may be important in determining the effect of drought on yield. Roots of the intermediate cycle wheats grow deeper into the soil profile, which in turn allows the extraction of water stored there (Hurd 1974, Meyer and Green 1980, Misra and Chaudhary 1985). There is little information relating to the effects of the relative timing of exposure to drought and the initiation of jointing. Much previous work has focused on the timing of flowering as a mechanism of drought escape (e.g., Fischer and Maurer 1978).

This poster reports the results of an experiment designed to examine the effects of early drought on the rooting patterns, water extraction profiles, and yield of three bread wheat cultivars that differ in growth cycle duration and when jointing occurs.

Materials and Methods

The experiment was done in 1988 at the National Institute of Agricultural Technology (INTA), Castelar, Argentina (34°40'S, 58°39'W). The cultivars used were Las Rosas INTA (LR), an intermediate-cycle wheat that commences jointing fairly early; Cargill Trigal 800 (T800), an intermediate-cycle wheat that joints somewhat later; and Marcos Juarez INTA (MJ), a short-cycle cultivar that also begins jointing rather late in the season. Anthesis of all three cultivars, sown at the appropriate times, takes place at about the same time. Two water regimes were used: irrigated throughout (R) and droughted (S) from August 12 (emergence of MJ) to October 7 (part-way through jointing of the three cultivars). This drought exposure schedule minimized any

possible advantage the short-cycle variety may have derived from reduced evapotranspiration during the interval between the sowing dates.

Seeds were sown in mini-drainage lysimeters (24-cm diameter, 150-cm deep) which contained a re-packed typic arguidol (55, 50, and 30 cm of the C, B, and A horizons, respectively), over a layer of fine pebbles. Drainage could be drawn up with a vacuum pump from the pebble layer through a permanently installed section of polyethylene tubing. Groups of nine lysimeters installed in a 150-cm deep well bordered by a crop whose seed was sown directly into the soil were assigned to each treatment (cultivar x water regime). Rain was excluded using moveable polyethylene-film shelters. Three lysimeters per group were equipped with horizontally-inserted probes for time-domain reflectometry (TDR) determination of the soil water content. A gantry fitted with a pulley could be placed over the well to lift the lysimeters out for measuring soil water content.

Seeds of intermediate cycle cultivars were planted in rows 12.5 cm apart on July 12; the short-cycle cultivar was planted on August 3. The lysimeters were overplanted and then thinned after emergence to 12 plants/lysimeter. Equivalent population density (including the voids between lysimeters in the estimate of ground surface area) was 220 plants/m^2. All treatments received a basal dressing of 60 kg N and 60 kg P/ha and a further dressing of 60 kg N/ha at the end of tillering. Weed control was manual and fungicide was applied at 2-week intervals during the grain-filling period.

Drainage water was extracted at weekly intervals from all lysimeters; measurements of soil water content were made with the same frequency on the three instrument-equipped lysimeters per treatment. Evapotranspiration (ET) per instrumented lysimeter was estimated from weekly records of irrigation, change in soil water content, and drainage. At the end of the drought, one lysimeter per treatment was harvested and root biomass in each layer for which the soil water profile had been measured was determined. A potted clump of wheat plants was used to fill the gap in the canopy left by the removal of this lysimeter. A record was kept of the timing of emergence, start of tillering, first visible node, anthesis, and maturity.

At maturity, all plants in each lysimeter were harvested and aboveground biomass and yield were determined. Some variables were subjected to statistical analysis (analysis of variance or Tukey test) as if the experiment was a fully randomized design with each lysimeter a replication. Yield was analyzed using the median polish technique of Tukey (1977).

Results and Discussion

Water use

Cumulative nominal ET estimates (uncorrected for lysimeter geometry effects on TDR estimates and for lysimeter/array surface ratio) for the irrigated intermediate cycle cultivars (LR, T800) were indistinguishable and exceeded those for the short cycle cultivar (MJ) (Figure 1). These effects are attributable, in part, to the later sowing of MJ. ET was significantly (P=0.05) reduced during exposure to drought in all three cultivars, recovery on re-watering was rapid (Figure 1). During exposure to drought, water consumption by the intermediate cycle cultivars was greatest, and after mid-September consumption by LR began to exceed that of T800. During the period of exposure to drought, relative ET (ETS/ETR) for the three cultivars was 53, 43, and 36%, for LR, T800, and MJ, respectively.

Differences in ET between the intermediate and short cycle cultivars were associated with differences in both canopy development (not measured) and rooting depth; differences between LR and T800 were associated with variations in the extraction of water from the deeper layers of soil (Figure 2). Significant (P=0.05) reductions of soil water content during the exposure to drought were observed in all soil layers (up to 125 cm) for both LR and T800, and only up to the fourth layer (100 cm) for MJ.

Root growth

Total root biomass and its distribution were affected by both treatment and cultivar (Figure 3). Total biomass decreased under both regimes in the order LR, T800, and MJ, and in all cultivars was consistently (NS, mean of three cultivars) reduced by drought. Detectable amounts of root biomass were found in the 125-150 cm layer in both LR and T800, while none were detected below 125 cm in MJ, under both R and S regimes.

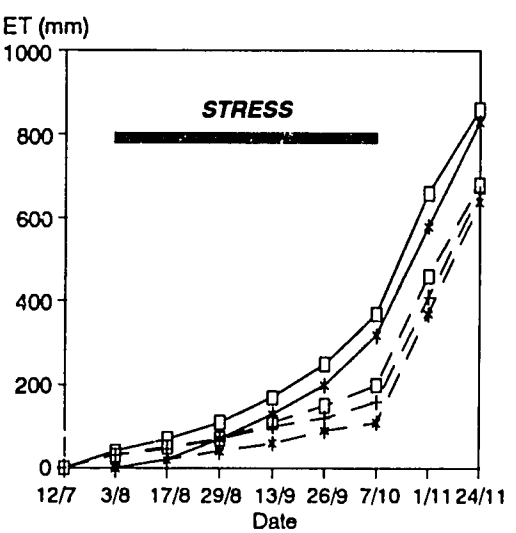

Figure 1. Cumulative evapotranspiration for irrigated (solid lines) and droughted (dashed lines) lysimeters (□LR), (+ T800), (* MJ).

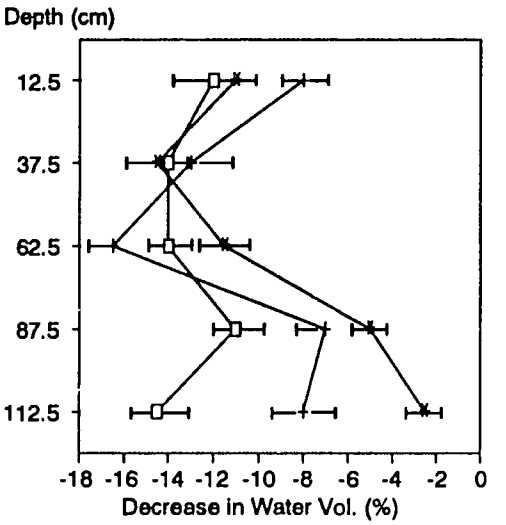

Figure 2. Decrease in soil volumetric water content during exposure to drought. (□ LR), (+ T800), (* MJ). Error bars are standard errors (n=3).

Drought produced a significant reduction (P=0.05, mean of three cultivars) in root biomass in the 0-25 cm layer, but consistently increased biomass in the lower layers. Exposure to drought increased root/shoot ratio in all three cultivars (Figure 4). The mean ratio increased from 0.29 to 0.46 (P=0.05, mean of three cultivars), indicating a substantial effect of drought on biomass partitioning.

Overlap between exposure to drought and phasic development

Tillering commenced earliest in T800 and latest in MJ, and jointing began later in the order LR, T800, and MJ (Figure 5). The whole of the tillering phase took place during exposure to drought in all three cultivars. The proportion of the jointing phase, which overlapped with drought, decreased in the order LR, T800, and MJ, whether expressed in calendar or thermal (Tb= 0°C) time (Table 1). Dates of end of jointing, flowering, and maturity were similar for all three cultivars (Figure 5).

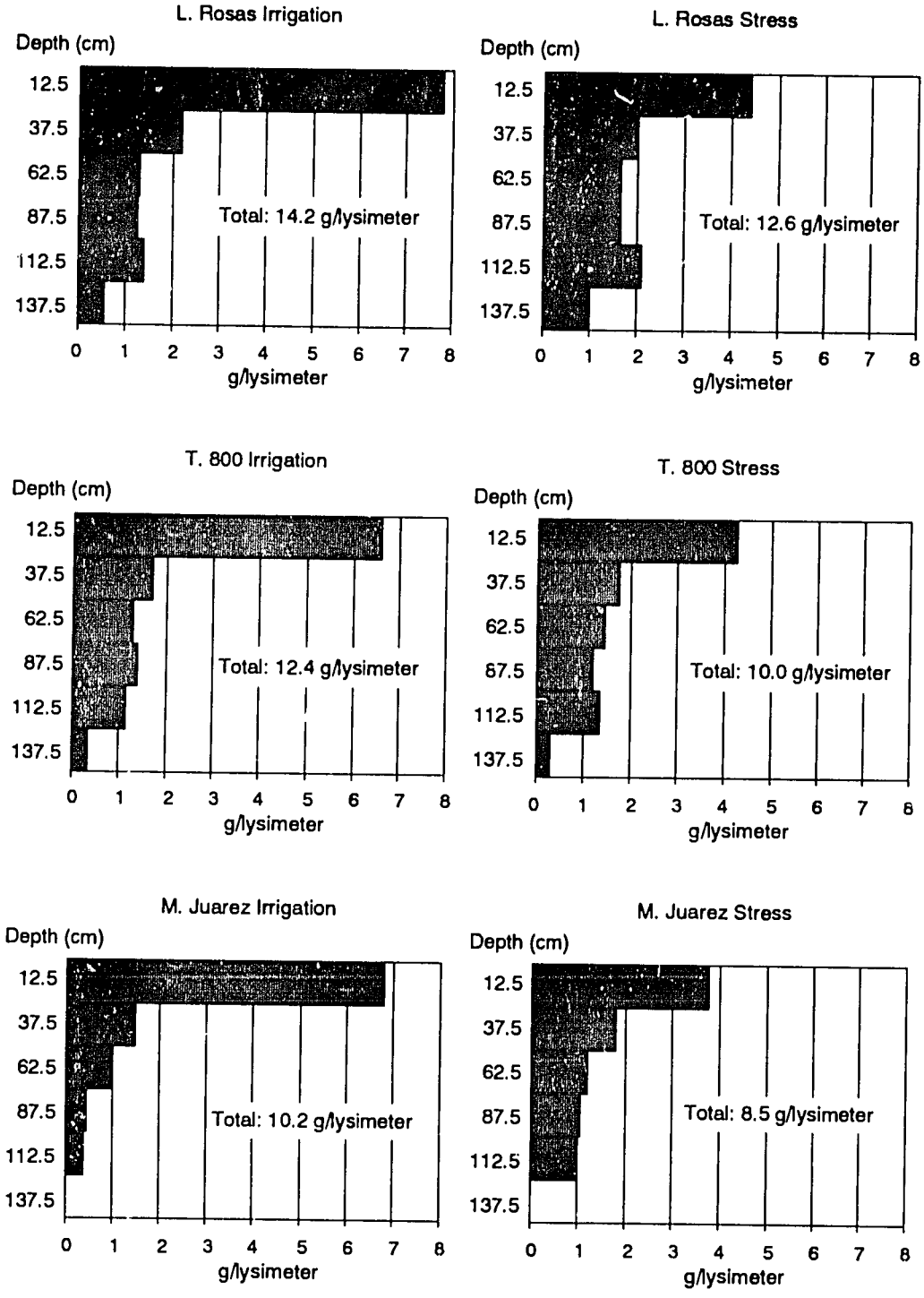

Figure 3. Root biomass profiles. Total values in each panel are total root biomass. Values derived from one lysimeter per treatment.

Yield

Figure 6 shows the yield for the six treatments plotted using the median polish technique (Tukey 1977). Diagonal lines marked LR, MJ, and T800 show the cultivar responses to water availability. Irrigated treatments (line R) showed no differences between cultivars, and under drought (line S) there was a significant reduction in yield of all three varieties. Cultivar x treatment interactions are shown by the lack of parallelism of the R and S lines, and in treatment S yield of T800 was significantly (P=0.05) greater than that of the other two cultivars.

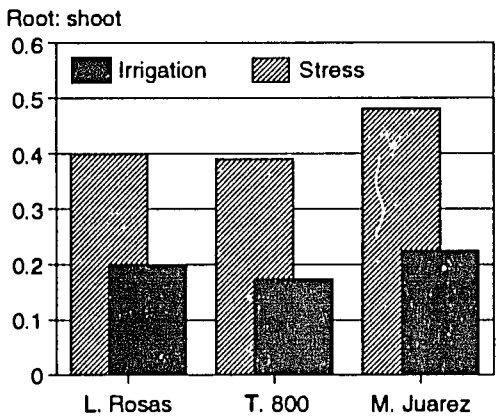

Figure 4. Root:shoot ratios in irrigated and droughted treatments. Values derive from one lysimeter per treatment.

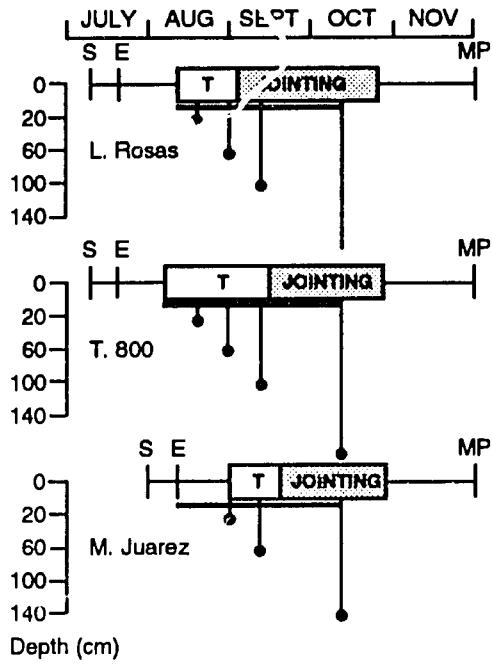

Figure 5. Phasic development and exposure to drought. S: Sowing; E: Emergence; MP: Physiological Maturity. Open and diagonally hatched bars show the tillering (T) and jointing (J) stages, respectively. The solid horizontal bar indicates the period of exposure to drought. Vertical bars terminating in a point show the advance of the water extraction front for three (M. Juarez) or for four dates.

Table 1. Overlap between jointing and exposure to drought expressed in calendar time (CT, days) and thermal time (TT, °Cd, base temperature 0°C).

Cultivar	Duration of exposure to drought during jointing		Proportion of jointing phase exposed to drought (%)	
	CT (days)	TT (°Cd)	CT	TT
L. Rosas	33	471	63	63
T. 800	21	320	53	54
M. Juarez	14	232	42	46

°Cd = degree days.

These results show that rooting depth and greater extraction of water from deeper soil layers, here associated with length of cycle, is insufficient to ensure, by itself, improved tolerance to early drought (cv. LR vs. MJ). It is generally accepted that the phases of rapid stem elongation and flowering are the most susceptible to drought (Aspinall et al. 1964, Morgan 1971, Wright 1972, Fischer 1973, Fischer et al. 1977, Innes and Blackwell 1981). Delayed jointing presumably contributed to the smaller effect of drought on T800 vis-a-vis LR (Figure 5, in spite of the fact that LR appeared to extract more water; Figure 2); but the combination of delayed jointing and decreased water extraction (MJ commenced jointing some 7 days after T800, but extracted less water, Figures 2 and 5) was not as effective as late jointing and deeper rooting.

These results raise a number of questions. Initial water storage was high throughout the profile, and under these conditions the intermediate cycle cultivars extracted more water from the profile. Whether this apparent advantage could be expected to hold under conditions of an incompletely filled soil profile at the start of the drought remains to be seen. Earlier sowing of an intermediate cycle crop may ensure greater rooting depth, but there is a trade-off in terms of greater water use. It will be necessary to examine the net result of this trade-off in relation to the water availability patterns characteristic of the various areas where early drought is a frequent phenomenon. Finally, increasing delays in jointing with a fixed anthesis date could conceivably reduce yield potential once a certain threshold is passed, and there is little information on this issue.

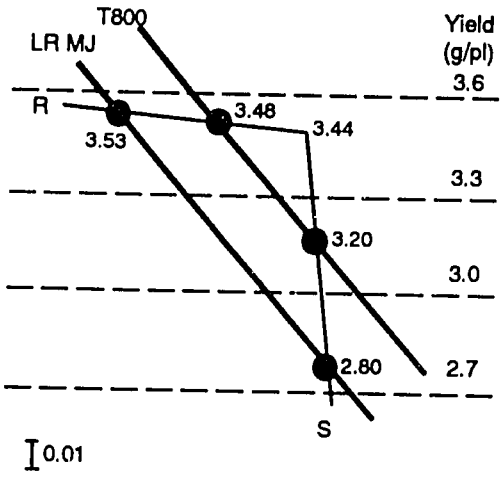

Figure 6. Water availability regime and cultivar effects on yield. Data plotted to conform with the median polish technique. Median values (n=8) separated on the vertical scale by more than the error bar are significantly different (P= 0.01).

Conclusions

- Under conditions of good initial soil water storage, intermediate cycle cultivars can extract more water because of greater rooting depth.
- Among cultivars with a similar capacity for water extraction, a delay in the commencement of jointing improves tolerance to early drought.
- Among cultivars with a similar timing for the start of jointing, a greater capacity for water extraction at depth improves tolerance to early drought.

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Resumen

Se examinaron los efectos de la sequía temprana (que abarca el macollamiento y principios del embuchamiento) sobre los patrones de enraizamiento, los perfiles de la extracción de agua y el rendimiento de tres variedades de trigo harinero. Estas variedades, de diferentes ciclos de cultivo (dos intermedias y una corta) y períodos de embuchamiento, se cultivaron en lisímetros para minidranaje, algunos de los cuales contaban con sondas de reflectometría de dominio temporal. Los dos trigos de ciclo intermedio tuvieron raíces más profundas y extrajeron más agua de los perfiles más profundos. La sequía redujo el rendimiento de todas las variedades, pero la variedad que combinó un inicio más tardío del embuchamiento y un enraizamiento profundo fue la menos afectada. El comienzo tardío del embuchamiento o el enraizamiento profundo por separado no fueron eficaces para reducir los efectos de la sequía.

Long-Term Fertility Effects on Wheat Productivity

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Abstract

Long-term fertilizer experiments established in India during 1970-71 indicated a declining trend in wheat productivity over the years—even under balanced application of NPK chemical fertilizers in multiple cropping systems. The deterioration in productivity was found to be associated with the emergence of deficiencies of secondary nutrients like sulfur and micronutrients like zinc. The normal recommended doses of NPK fertilizers for wheat were found to be suboptimal when applied to multiple cropping systems involving rice or maize, thereby suggesting that the fertilizer recommendations should be developed on a cropping systems basis for realizing greater wheat productivity. The integrated use of organic manures and chemical NPK fertilizers was found to be quite promising, not only in providing greater stability in production, but also in maintaining higher soil fertility status.

Introduction

Tremendous progress has been witnessed in food production throughout the world since the middle of the 20th Century. The major concern now is whether such increases in food production can be sustained. It was in this context that the Indian Council of Agricultural Research initiated the All-India Coordinated Research Project on Long-Term Fertilizer Experiments during 1970-71. Eleven sites were used representing major soil and climatic zones of the Indian Subcontinent.

This poster reports the long-term soil fertility effects on wheat productivity in multiple cropping systems under some soil-climatic situations in India. The experimental and supplementary details are documented in the Project's Research Bulletin No. 1 (Nambiar and Ghosh 1984).

Major Nutrients and Wheat Productivity

The mean productivity of wheat in multiple cropping systems as affected by the major nutrients is shown in Table 1.

The application of N fertilizer alone to soils had a short-term effect on wheat productivity, especially on soils with low native P and K fertility. Fertilizer N failed to produce a response on acid soils in the absence of P fertilizer and the productivity of wheat was lower than that on the unmanured plots (Figure 1). The

Table 1. Mean grain yield of wheat (t/ha) at selected locations between 1971 and 1987 where chemical fertilizers were applied.

Location	No fertilizer	N	NP	NPK
Barrackpore (West Bengal)	0.8	2.1	2.3	2.3
Delhi	2.1	3.3	3.8	4.3
Ludhiana (Punjab)	0.9	2.7	4.0	4.7
Jabalpur (Madhya Pradesh)	1.1	1.6	3.7	3.9
Ranchi (Bihar)	1.2	0.6	2.3	2.5
Palampur (Himachal Pradesh)	0.4	0.7	2.1	2.6
Pantnagar (Uttar Pradesh)	1.8	3.9	3.9	4.0

deterioration in wheat productivity with continuous dressing of N fertilizer over the years was found to be associated with the increase in acidity resulting in increased activity of Al^{3+} and Fe^{3+} thereby inhibiting the nutrient uptake, mainly of P (Nambiar 1985).

The productivity of wheat declined considerably in the absence of P fertilizer as the native available P (bicarbonate-extractable P) dropped down to a level less than 5 mg/kg soil.

The effect of K fertilizer was quite marked on soils with low available K, while it was small on soils with high available K. However, there was an increasing response to K fertilizer with the depletion of readily available soil K.

Secondary and Micronutrients and Wheat Productivity

The influence of sulfur on wheat productivity was quite marked in recent years as a result of the intensive use of highly concentrated S-free NPK fertilizers in addition to the increased uptake of S in intensified cropping systems. The effect of S on wheat productivity became evident (Figure 2) as the available S (Morgan's extractable S) dropped to 4-5 mg/kg soil.

Deterioration in wheat productivity was also found to be due to the emergence of Zn deficiency (Figure 3) and productivity was returned to the original level with the application of Zn either as a foliar spray or soil incorporated.

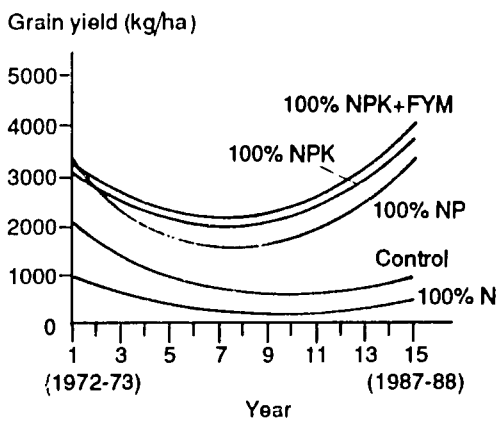

Figure 1. Yield trend of wheat on red loam, Ranchi Center.

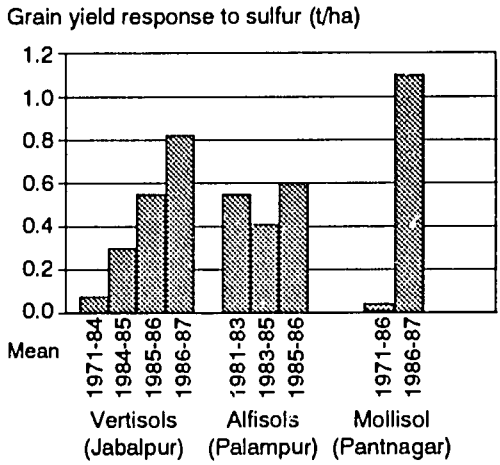

Figure 2. Yield response of wheat to sulfur (over optimal NPK dose) in ICAR LTF experiments over the years (1971-87).

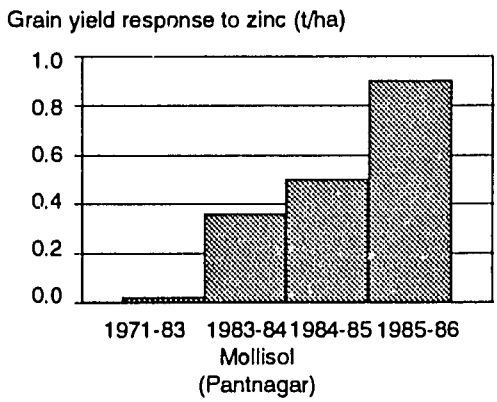

Figure 3. Yield response of wheat to zinc (over optimal NPK dose) in ICAR LTF experiments over the years (1971-86).

Inadequacy of Wheat Fertilizer Recommendations

The normally recommended rates of NPK fertilizers to wheat were found to be suboptimal in multiple cropping systems, particularly with rice or maize in the rotation (Table 2).

Significant responses to increased NPK application were obtained on a Eutrochrept (Barrackpore), a Hapludalf (Palampur), and a Hapludoll (Pantnagar) where either rice or maize was grown in the multiple cropping systems (Nambiar 1986), suggesting the need for developing the fertilizer recommendations on a cropping systems basis.

Wheat Productivity under Integrated Organic and Inorganic Manuring

The long-term experiments have shown that neither organic manures alone nor chemical fertilizers can achieve sustainability in production. However, the integrated use of organic manures and chemical fertilizers was found to be quite promising in maintaining stability in crop production (Table 3) through correction of marginal deficiencies of secondary and micronutrient elements in the course of mineralization on one hand and providing favorable physical and soil ecological conditions on the other.

Table 2. Effect of graded rates of NPK fertilizers on the yield of wheat during the 1971-87 period.

Location	Mean grain yield of wheat (t/ha)	
	100% NPK	150% NPK
Barrackpore	2.3	2.9
Delhi	4.3	4.7
Jabalpur	3.8	4.2
Palampur	2.6	3.1
Pantnagar	3.9	4.5

Table 3. The effect of integrating organic and inorganic manuring on wheat productivity (t/ha).

	Mean grain yield			
	(1984-87)		(1971-87)	
	150% NPK	100% NPK + FYM	150% NPK	100% NPK + FYM
Ludhiana	5.3	5.3	4.7	4.8
Jabalpur	4.3	4.6	4.2	4.3
Ranchi	3.1	3.4	2.4	2.6
Palampur	3.3	4.0	3.1	3.3
Pantnagar	4.4	5.3	4.6	4.7

FYM = farm yard manure

Plant Nutrient Balance

The mean annual plant nutrient balance (N, P, and K) over the years (1971-87), computed as the difference between the inputs (nutrients applied) and the outputs (nutrient uptake), indicated that the balance of P was positive (Figure 4) at optimal (100%) to superoptimal (150%) NPK applications on most of the soils where the mean annual grain production varied from 6 to 7 t/ha. However, it was negative on highly productive soils such as Hapludoll at Pantnagar where the mean annual grain production was more than 10 t/ha. The balance of K was negative even at the superoptimal NPK application (150%) on most of the soils (Figure 4). There was a close balance in K with NPK+farm yard manure (FYM) treatment on an acid Haplustalf (Ranchi) where the productivity was comparatively low (less than 7 t/ha).

Long-Term Effects of Intensive Cropping and Manuring on Soil Fertility

Soil pH

Continuous dressing of N fertilizer alone resulted in decreased productivity, particularly on acid soils due to increased acidity. This has led to the accumulation of Al^{3+} and Fe^{3+} to toxic levels. In contrast, increases in soil pH were observed on certain other soils resulting in reduced availability of micronutrients (e.g., zinc). The increase in soil pH was attributed to depletion of available K and its partial replacement by Na^{+} ions through irrigation water.

Soil organic carbon

The role of soil organic carbon in maintaining soil fertility and productivity is well recognized. A marginal improvement in soil organic carbon content was noted with the balanced use

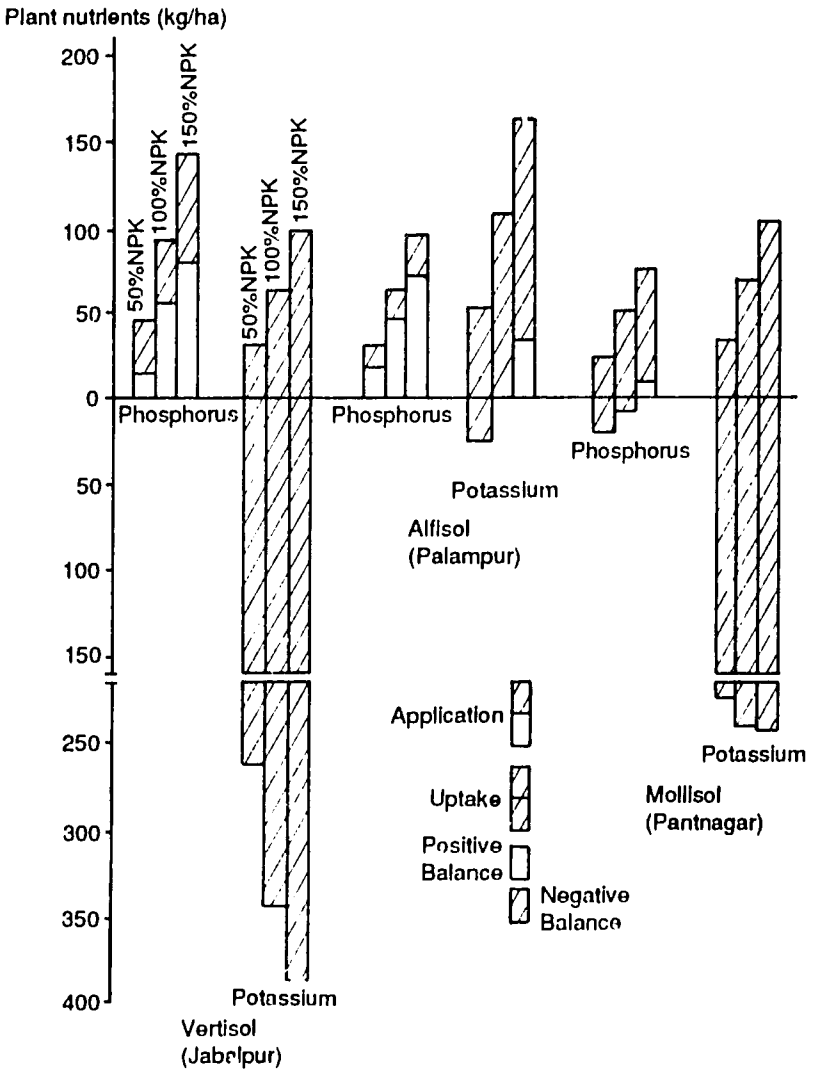

Figure 4. Phosphorus and potassium nutrient balances over the period 1971-87 in ICAR long-term fertilizer experiments.

of NPK fertilizers on almost all the soils. However, the highest C content was noted in the case of integrated use of organic manures and chemical NPK fertilizers (Table 4).

Available soil N, P, K, S, and Zn

Nitrogen—Application of N at optimal rates over the years (1971-1987) resulted in increases in available N over the initial levels on almost all the soils, particularly where NPK+FYM was applied.

Phosphorus—Continuous addition of P fertilizer at optimal rates raised the available P appreciably over the years (1971-87) on almost all the soils. However, there was only a marginal P buildup on a Chromustert (Jabalpur) even after 17 years of P addition, suggesting the need for more P application to these soils. The highest P buildup was obtained under NPK + FYM treatment.

Table 4. Change in soil organic carbon content (%) during the 1971-87 period.

Location	Initial value	Treatment	
		100% NPK	100% NPK + FYM
Barrackpore	0.71	0.44	0.62
Delhi[a]	0.44	0.52	0.56
Ludhiana	0.21	0.26	0.40
Jabalpur	0.57	0.50	0.84
Ranchi	0.45	0.35	0.40
Palampur	0.79	0.94	1.31
Pantnagar	1.48	1.03	1.56

[a] After 10 annual cropping cycles.

Potassium—The application of K fertilizer at optimal rates from 1971 to 1987 improved the available soil K marginally. However, depletion in available soil K was observed on a Chromustert even at the superoptimal rate. The K balance study indicated that there was inadequate K application to soils leading to considerable draw down in available soil K.

Sulfur—A marked improvement in available S was noted over the initial level on almost all the soils where S-containing NPK fertilizers were applied. However, the available S dropped down to below the critical level (5-7 mg/kg) where S-free NPK fertilizers were applied.

Zinc—The available Zn dropped to low levels where Zn fertilizers were not applied and the productivity of wheat was adversely affected .

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Resumen

Los ensayos prolongados con fertilizantes, realizados en la India durante 1970-1971, revelaron una tendencia descendente en la productividad del trigo en el transcurso de los años, aun con la aplicación equilibrada de fertilizantes químicos NPK en sistemas de cultivos múltiples. Se encontró que el deterioro de la productividad se debía a la aparición de carencias de nutrimentos secundarios como el azufre y micronutrimentos como el zinc. Se observó que las dosis normales recomendadas de fertilizantes NPK eran subóptimas cuando se las aplicaba a sistemas de cultivos múltiples que incluían el arroz o el maíz, lo cual indica que, para lograr una mayor productividad del trigo, las recomendaciones sobre fertilizantes se deben formular de acuerdo con el sistema de cultivo. El uso integrado de abonos orgánicos y fertilizantes químicos NPK resultó muy promisorio, no sólo porque proporcionó mayor estabilidad en la producción sino también porque mantuvo una mayor fertilidad del suelo.

Environmental Limitations for the Expression of the Yield Potential of Wheat in North Thailand: A Preliminary Investigation

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Abstract

The photo-thermal quotient adequately predicted the potential yield of wheat in this region. The rapid rates of growth in these hot regions, however, greatly reduce the compensation ability of wheat and, thus, any shortfalls in establishment or in early growth due to nonoptimal agronomy lead to a large yield penalty. The yield index of Woodruff and Tonks (1983, Australian Journal of Agricultural Research 34:1-11) explained 80% of the variation between genotypes or drought and nutrient treatments in trials with no apparent disease incidence. Significant genotype differences in establishment and early growth, which continued until anthesis, were identified. These were well related to germination and vigor tests conducted for 3 days at 30°C in controlled environments.

Studies of wheat (*Triticum aestivum* L.) growth, development, and grain yield were monitored in a number of fully irrigated and dryland trials, undertaken by various Thai research scientists during 1988. Measurements were taken at anthesis of available soil water, root distribution, above ground biomass, and leaf area. The major conclusions from these studies, albeit of a preliminary nature, are:

- The yield potential at most of the sites examined in northern Thailand was "adequately" predicted by the photo-thermal quotient (Nix 1976). The optimal flowering time was late December-early January with a yield potential of 3.5 to 4.2 t/ha. The maximum yield obtained at sites with an effective soil depth of > 60 cm and full disease control was within 20% of the predicted optimal.

- Genotype variation in maximum yields obtained at the various sites was very low, due presumably to the lack of genotypic variability in the rate of development in the critical stage from female meiosis to anthesis. Significant genotype differences, when they occurred, were correlated with differences in emergence percentage, anthesis date, or differential responses to nutrient application or disease incidence.

- Yields were well correlated (Figure 1) with the yield index model of Woodruff and Tonks (1983) and, at most sites, the leaf area function of this model was the dominant determinant of yield variation.

- Small deviations from optimal growing conditions and/or agronomy caused severe yield reductions. These appeared to be due to the low compensation between yield components under the fast development rates caused by elevated temperatures. This lack of compensation was shown by the strong correlations (r) between plant number (0.55), tiller number (0.73), and leaf area index (LAI) (0.80)—all measured at anthesis—and final grain yield.

- Substantial variation within the gene pool was found for % establishment and early leaf growth. These were related to coleoptile length, seed size, and the area of the first two leaves.

Table 1 presents the extremes found from an initial laboratory screening of over 200 genotypes. The extreme range of both root and coleoptile lengths found in laboratory tests suggest real genotype differences for these characteristics. There was good correlation, at least with these extremes, between laboratory and field testing with the exception of cv. Cocorit whose slow rate of germination in the laboratory caused its misranking as determined by field data. Laboratory tests of wheats (at 35°C for 4 days)

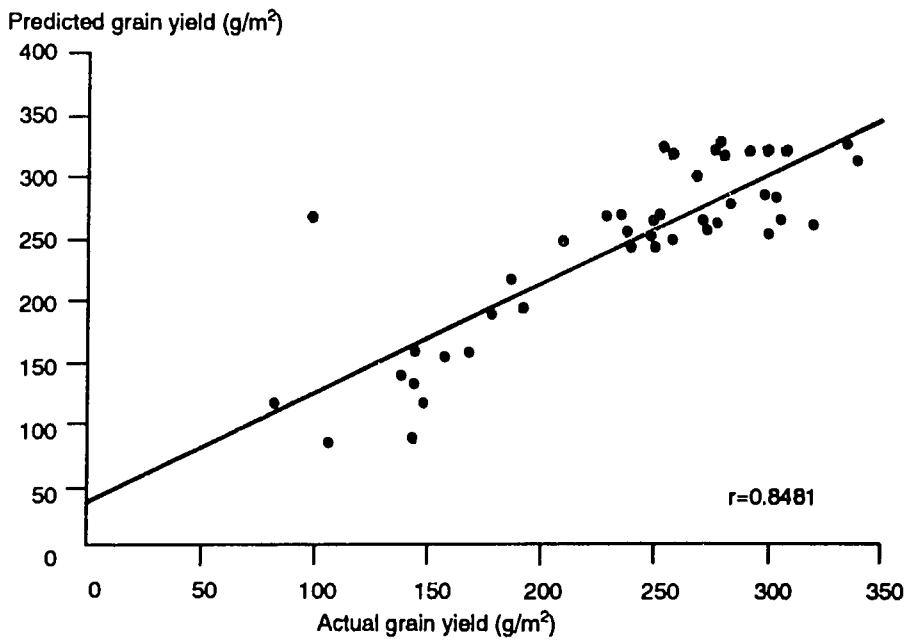

Figure 1. Actual vs. predicted grain yield, Lampang, Thailand.

Table 1. Results of emergence tests in the laboratory and the field.

Test variety[a]	Germination tests (3 days) 30°C Root (cm)	30°C Coleopt. (cm)	35°C Root (cm)	35°C Coleopt. (cm)	% Final emergence of 50 seeds from field plots (3 reps) at sowing depths: 2 cm	3.4 cm	4.0 cm
Jupateco	5.2	0.8	2.7	1.5	88a	76a	68ab
SW39	4.7	0.9	2.6	1.4	76a	68ab	59bc
CMU246	4.2	0.8	1.9	1.5	88a	68ab	58ab
CMU24	1.6	0.3	1.0	0.2	76a	48bc	10d
SW9	1.3	0.3	1.0	0.3	90a	35c	0d
Cocorit	1.0	0.1	1.5	0.3	70ab	64b	44c

[a] Test varieties were chosen to provide extremes of results from laboratory measures of over 200 genotypes.

Data followed by similar letters, LSD P > 0.05.

could be worthwhile for wheats selected for growth in hot climates where the LAI at anthesis is often limiting.

- Preliminary measurements of root density indicated, especially in crops grown after rice, extreme spatial variation. There was some indication (i.e., a single trial) that the rate of root penetration to depth was substantially enhanced by zero tillage.

The above results were drawn from a single year of observations and are thus are only preliminary. They do suggest that measurement of plant, soil, and meteorological parameters around flowering could be useful as integrative tools to explain the variation in results in these regions.

Acknowledgments

I am deeply indebted to Drs. Maneepong and Ngamchuen of Kasetsart University, Drs. Benjavan and Mehti of Chiangmai University, Drs. Sawit and Narong and other staff at LARTC, Lampang, and to Dr. Somrith and Walaiporn at Phrae. Without their support and kind cooperation in allowing me to use their trials, these studies could not have been conducted. I also wish to acknowledge all those Thai research scientists and farmers unnamed, who freely provided their deep knowledge of their environments. Financial and other support was generously supplied by Queensland Wheat Research Committee and CIMMYT.

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Resumen

El cociente fototérmico permitió pronosticar adecuadamente el potencial de rendimiento del trigo en esta región. Sin embargo, la rapidez del desarrollo en estas regiones calurosas reduce en forma considerable la capacidad de compensación del trigo y, en consecuencia, toda deficiencia en el establecimiento o el desarrollo temprano causada por una agronomía no óptima provoca un gran efecto negativo sobre el rendimiento. El índice de rendimiento de Woodruff y Tonks (1983, Australian Journal of Agricultural Research 34:1-11) explicó el 80% de la variación entre los genotipos o la sequía y los tratamientos con nutrimentos en ensayos donde no hubo una incidencia evidente de enfermedades. Se identificaron diferencias significativas entre los genotipos en cuanto al establecimiento y al desarrollo temprano, que continuaron hasta la antesis. Esas diferencias coincidieron con los resultados de las pruebas de germinación y de vigor efectuadas durante tres días a 30 °C en ambientes controlados.

Wheat Cultivation in Nigeria: Problems, Progress, and Prospects

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Abstract

Wheat is produced in Nigeria entirely under irrigation within latitudes 10 to 14°N where night temperatures during most of the growing period (November-March) range from 10-15°C. The mean maximum temperature ranges from 30 to 35°C. Varieties recommended for cultivation are Samwhit 1 (Tousson), Samwhit 2 (Florence Aurore 8193), Samwhit 3 (Sonora 64), Samwhit 4 (Lee//N10/B/3/GB55/4/GB56), and Samwhit 5 (Siete Cerros). Recently recommended are Samwhit 6 (Pavon F.76), Samwhit 7 (Bulbul), and Samwhit 8 (Sonalika). Resulting from the ban on wheat importation into Nigeria, effective January 1987, local wheat production rose from about 50,000 t/year to an estimated 150,000-180,000 t/year. Some of the major problems facing wheat production in the country and the prospects of producing a high proportion of its need are highlighted.

Introduction

Wheat is produced in Nigeria entirely by irrigation and is presently restricted to the area between latitudes 10-14°N (Figure 1) where night temperatures are in the range of 10-15°C during most of the growing period (November-March). Table 1 shows the average minimum and maximum temperatures during the period for Samaru, located at latitude 11°11'N. The absolute minimum and maximum temperatures during the period range from between 5-8°C and 30.0-32.5°C, respectively.

The Institute for Agricultural Research (IAR), Ahmadu Bello University, Zaria, began wheat research in Nigeria in 1959.

Table 1. Mean minimum and maximum temperatures of Samaru (Lat. 11°11'N).

	Nov.	Dec.	Jan.	Feb.
Minimum Temp. (°C)	15.1	14.0	14.0	15.6
Maximum Temp. (°C)	31.4	30.8	30.2	31.0

The objectives of this research program have been to identify cultivars of bread wheat that, under Nigerian conditions, are high yielding, responsive to fertilizer application, resistant to diseases, and of good breadmaking quality.

Until the ban on wheat importation into Nigeria in January 1987, almost all the wheat and wheat products required in the country were imported. Importation rose rapidly from about 407,500 tons in 1975 to 1.83 million tons in 1985, which brought about a huge drain on the country's foreign exchange reserves.

Progress

Crop improvement

Attention has been focused on the screening of varieties/lines suitable for cultivation in Nigeria and meeting the objectives stated above.

In 1965 Samwhit 1 (Tousson) and Samwhit 2 (Florence Aurore 8193) were recommended for yield and bread making quality, respectively. In 1971 two Mexican varieties, Samwhit 3 (Sonora 64) and

Samwhit 4 (Lee//N10/B/3/GB55/4/GB56) were released. These are semidwarf, earlier maturing, more resistant to lodging, and more responsive to fertilizer than Tousson and Florence Aurore 8193. In 1974, Samwhit 5 (Siete Cerros), which is high yielding and of average bread making quality was released. In 1990, three additional Mexican varieties were released—Samwhit 6 (Pavon-76), for its high quality; and Samwhit 7 (Bulbul) and Samwhit 8 (Sonalika), both for their earliness. With good management practices, these varieties can produce about 3-4 t/ha. Samwhit 5 (Siete Cerros) is the most widely planted wheat variety in the country.

Agronomic practices

A package of agronomic practices suitable to the above varieties has been developed. These practices include sowing date, sowing rate, water management, and fertilizer application. However, few farmers are adopting these recommendations.

Rainfed wheat

Efforts have been underway to identify wheat varieties capable of performing well under rainfed conditions in Nigeria, but they have not been very fruitful. Because of the relatively high temperatures throughout the period, rainfed wheat exhibits poor tillering, has light and sometimes shrivelled grains, is very

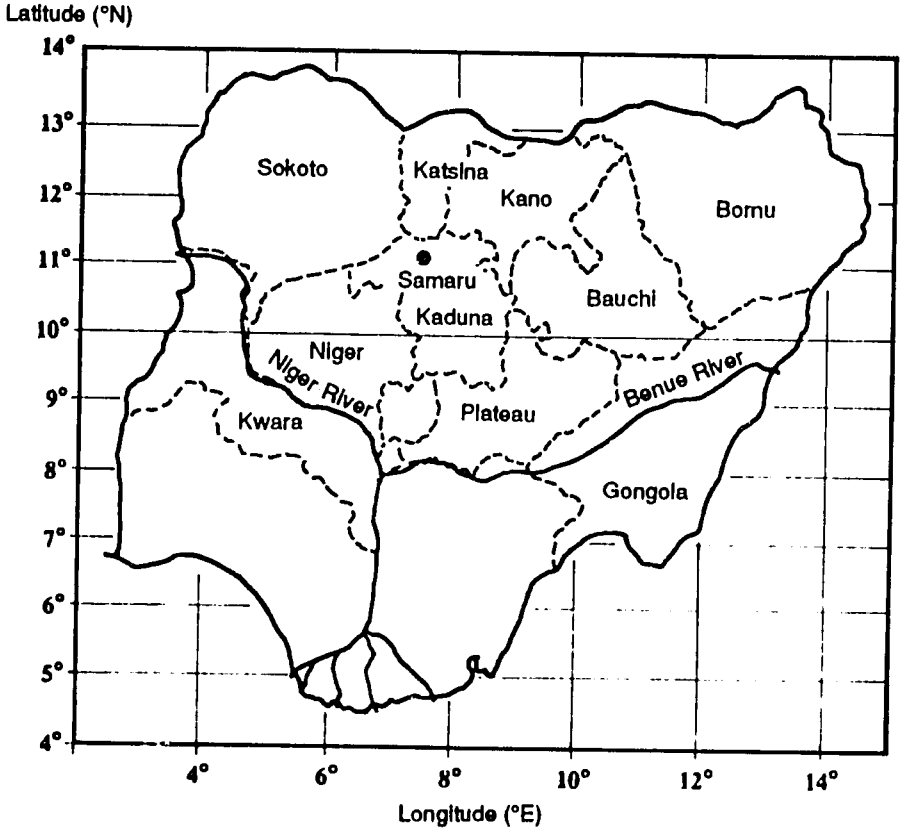

Figure 1. Nigeria, showing the wheat producing (Lat. 10-14°N) and bordering states.

susceptible to fungal attacks especially by *Fusarium* spp. and *Helminthosporium sativum*, and, consequently, yields are low and grain is of poor quality.

Recently, the Lake Chad Research Institute, Maiduguri, Nigeria, has identified a few varieties that are capable of performing reasonably well at high elevations, such as the Mambilla Plateau where temperatures are relatively low throughout the year. However, such areas are very limited in the country.

Level of production

The country's wheat production drive can best be quantified in terms of its present level of production. According to the figures supplied by the States, about 214,000 ha of land were planted to wheat during the 1988-89 crop season (Table 2). With an estimated average yield of 2 t/ha, a total of 428,000 tons of wheat may have been produced during that season. While the actual production figure is somewhere between 150,000 to 180,000 t/year, this is still a remarkable increase over the estimated 50,000 t/year that was produced before the importation ban. This production level should continue to rise in the years ahead.

Problems

Some of the major problems associated with wheat production in Nigeria have been recently highlighted (Olugbemi 1990). These include:

- Unsuitable climatic conditions.
- Unavailability of irrigated land.
- Unavailability of improved seed.
- Sowing of mixed seeds.
- Late sowing.
- Nonadoption by farmers of recommended agronomic and management practices such as appropriate seed and fertilizer rates and good water management.
- Severe shortage of suitable farm equipment, especially tractors and combine harvesters.
- Inadequate support for research.

Here, only a few of these will be briefly discussed.

Table 2. Area under wheat production by state in Nigeria, 1988-89 season.

State	Proposed area (ha)	Actual area cultivated (ha)	% Actual area cultivated	Average yield (t/ha)
Kano	200,000	174,914	81.78	2.5
Katsina	25,000	13,400	6.27	n.a
Borno	10,000	11,246	5.26	2.5
Sokoto	6,230	5,093	2.38	1.5
Bauchi	5,000	4,500	2.10	2.3
Kaduna	10,000	2,600	1.22	2.0
Niger	-	800	0.37	2.2
Plateau	300	502	0.24	1.8
Kwara	-	500	0.23	2.2
Gongola	57,000	328	0.15	2.5
Total	313,530	213,881	100.00	2.2

Source: Figures supplied by the States at the National Meeting on Wheat Production, Kano, 14 March 1989.

Unsuitable climatic conditions
Nigeria extends between latitude 4 and 14°N and therefore falls entirely within the tropics and, as earlier mentioned, only the area between 10-14°N and mainly altitudes between 240-360 masl are presently suitable for commercial wheat production. The country's high temperatures throughout the year, coupled with high humidity, renders the area outside this narrow zone unsuitable. To expand wheat cultivation in Nigeria, varieties that are more tolerant to heat and humidity than the existing ones are needed. Availability of such varieties, will make it possible to grow wheat under rainfed conditions in the lowlands as well as extending the area of cultivation under irrigation beyond the present narrow zone. Because of the current ceiling imposed on wheat yields in Nigeria by climatic conditions, especially temperature, the potential yields of the existing varieties under optimum management are much lower than those obtained elsewhere with lower temperatures.

Mixed seed
Many Nigerian wheat farmers do not make adequate arrangements for their seed requirements. Because of the pressure to obtain cash to meet their various obligations, they usually sell all their produce immediately after harvest and then have to resort to buying their seed at sowing in the open market. Such seed is usually highly mixed and poor in germination and quality and the resulting mixed crop presents harvesting problems. Although there is a national organization, the National Seed Service, charged with the responsibility of seed production for major crops including wheat, it cannot meet the needs of the farmers.

Late sowing
The recommended time for sowing wheat in Nigeria is from November into early December. Due primarily to the late removal of the preceding rainfed crop (e.g., rice and cowpea) and lack of access to suitable farm implements such as tractors, many farmers sometimes will sow their wheat as late as the end of January. Such crops usually develop and ripen very quickly under the prevailing high temperatures, resulting in poor yields.

Prospects

The average wheat yield in Nigeria is possibly in the range of 1.0-1.5 t/ha. If the national average yield can be increased to 2.5 t/ha, the nation's annual production on presently developed land would rise to about 500,000 tons. Sowing at the recommended time alone could possibly bring about 50% of this desired increase. Also, if the present keen interest in the development of "fadama" (fertile land bordering some streams) generated by the State governments and farmers can be maintained, substantial increase can be expected in the wheat area planted. Furthermore, the work done by the IAR, Zaria has shown that sorghum or maize can be mixed up to 30% with wheat to produce acceptable bread at the commercial level (Olugbemi 1988). All these will enhance the country's ability to produce a high proportion of its wheat requirement.

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Resumen

En Nigeria todo el trigo se produce con riego entre los 10 y 14° de latitud N, donde las temperaturas nocturnas durante la mayor parte del período de cultivo (noviembre-marzo) fluctúan entre los 10 y 15 °C. La temperatura máxima media varía entre 30 y 35 °C. Las variedades recomendadas para el cultivo son Samwhit 1 (Tousson), Samwhit 2 (Florence Aurore 8193), Samwhit 3 (Sonora 64), Samwhit 4 (Lee//N10/B/3/GB55/4/GB56) y Samwhit 5 (Siete Cerros). Recientemente se han recomendado Samwhit 6 (Pavón F.76), Samwhit 7 (Bulbul) y Samwhit 8 (Sonalika). Como resultado de la prohibición de importar trigo a Nigeria, efectiva a partir de enero de 1987, la producción local del cereal se elevó de unas 50,000 t anuales a una cantidad estimada en 150,000-180,000 t al año. Se destacan algunos de los principales problemas que afronta la producción de trigo en el país y las perspectivas de producir una proporción elevada de la cantidad necesaria del cereal.

Cytogenetics and Biotechnology to Accelerate Wheat Breeding in Southern Brazil: Production of Synthetic Hexaploids from Related Species and Doubled Haploids from Anther Culture

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Abstract

Wheat breeding in southern Brazil presents many problems related to several biotic and abiotic stresses that cause important crop losses. Cytogenetics and biotechnology techniques are useful in speeding up breeding work. At the National Research Center for Wheat (CNPT), EMBRAPA, crosses were made between T. durum *(AABB, 2n=28) and* Aegilops squarrosa *(DD, 2n=14), followed by chromosome counting and colchicine treatment of embryo cultured hybrids (ABD, 2n=21). Eleven hexaploid synthetic homozygous lines (AABBDD, 2n=42) were produced that are providing a quick and easy method for transferring, in about 12 months, good traits from both parental species to the hexaploid level. Double-haploids (DH) lines may be harvested in about 20 months after anther culture of F_1 populations. Around 1000 DH lines were produced at CNPT. The great majority of the DH lines were derived from germplasm of breeding project aimed at adaptation to humid climates. This germplasm also exhibited good andogenetic capacity (a.c.). Accurate breeder choices of donor plants in double, triple, or BC F_1 populations from crosses involving a.c. DH lines, synthetic hexaploids, and nonandrogenetic cultivars make it possible to derive good and variable homozygous lines, reducing breeding time, even with limitations for a.c. F_2 seeds may be returned to breeders to follow conventional procedures. Three of the best DH lines coming from F_1s in 1984 (PF 843025, PF 853083, and PF 853031) are now in final testing with yields of 18, 19, and 21% above the best check variety.*

Introduction

Wheat breeding in southern Brazil presents many problems because of stresses that cause important crop losses. The main stresses are:

- Aluminum and manganese toxicity in the soil.
- Stem and leaf rusts.
- Sporadic severe epidemics of necrotrophic diseases such as helminthosporium, septoria, and fusarium.
- Prolonged rains and cloudy days causing waterlogging and radiation stresses, which also favor fungal attacks.
- Strong winds in the spring.
- Drastic temperature fluctuations at flowering in which the temperatures can drop about 20°C in less than 24 hours, often followed by severe frosts causing partial or complete sterility.

Good levels of genetic resistance and/or tolerance to necrotrophic diseases and abiotic stresses are not yet available in

commercial cultivars or are not sufficient to avoid important crop losses in bad years.

Since the period required to combine many genes in productive and adapted lines is very long, any method which can help accelerate and simplify breeding work will be important in southern Brazil, despite the fact that, in recent years, new cultivars and improved cultural practices increased productivity.

Recently developed biotechnological techniques provide an opportunity to integrate breeding programs and biological disciplines to contribute to genetic improvement of cultivated plants. New techniques can result in a comparatively greater increase in productivity for developing countries because actual yields are relatively lower than in developed countries. In 1975 the National Wheat Research Center (CNPT) of the Brazilian Research Enterprise (EMBRAPA) began operation of its Cytogenetics Laboratory to support the breeding program. Partial results concerning two main projects will be presented here in this poster:

- The production of synthetic hexaploid lines as part of the project to transfer useful genes from wild species. This began in 1978 through the consultancy of Dr. E. Kerber from the Winnipeg Experimental Station in Canada, sponsored by the Canadian International Development Agency (CIDA).

- Anther culture for haploid production, which began in 1980 through the consultancy of Dr. E. Picard, from Orsay, Université Paris-Sud, France, sponsored by the Food and Agriculture Organization (FAO).

This poster emphasizes the importance of both methods (synthetic hexaploids and haploid production) to speed up breeding work as well as some practical results obtained at CNPT.

Synthetic Hexaploid Lines

Triticum aestivum L. Thell is a hexaploid species with a genomic constitution designated AABBDD and 2n=42 chromosomes, each seven homologous pairs being derived from three distinct diploid ancestral species. Sporadic natural crosses between different species followed by chromosomal duplication of hybrid plants was the evolution mechanism of the genus *Triticum*, which may be called a polyploid complex. There is extensive literature about the complexities of the genus at genetic and taxonomic levels. Elegant chromosome engineering work has been done to clarify the origin and evolution of *Triticum* and its relatives in the Triticeae (Sears 1956, 1972; Kerber 1964; Riley 1965; Kihara 1975; MacKey 1975; Kimber 1977; and Cauderon 1981).

Many useful genes for several biotic and abiotic stresses were transferred from related species. All these contributions were possible because of the continuous work of research groups throughout the world over the past decades (Sears 1956, 1965; Riley and Kimber 1966; Kerber and Dyck 1969, 1973; Law 1969; Knott and Dvorak 1976; Sharma and Gill 1983; and Cauderon 1988).

The transfer of useful genes from related species will be easier if they are in genomes homologous to hexaploid wheat because of crossing over and possibility of a consequent genetic recombination. The screening of a collection sent by Dr. E. Kerber and the Beltsville Laboratory (more than 1000 entries) showed *Aegilops squarrosa* L (2n=14, DD) was the species best adapted to local conditions with genes for resistance to fungal diseases.

Using the procedures developed by MacFadden and Sears (1944), it is possible to obtain a homozygous hexaploid line in about 10 to 12 months. Crosses are made using a tetraploid species (AABB, 2n=28) as a "bridge" and *Aegilops squarrosa* (DD, 2n=14). About 12 days after pollination, the hybrid embryos are cultivated in orchid agar at room temperature and the seedlings (ABD, 2n=21) are treated with colchicine to restore fertility. Breeders can immediately use the new hexaploid line (AABBDD, 2n=42), made in one step.

At CNPT, 11 hexaploid synthetic lines were obtained, eight of which have greater levels of resistance to stem rust than SR33, a source of resistance also derived from *Aegilops squarrosa*. Powdery mildew and leaf rust resistance were also obtained and fusarium resistance is being confirmed (Moraes-Fernandes and Linhares 1988, Moraes-Fernandes et al. 1988a,b).

Double Haploids Derived from Anther Culture

The technique of developing a haploid plantlet from pollen grain started when Guha and Makeswari (1964) observed embryoids in anther cultures of Datura. If anthers of F_1 plants are cultured, haploid embryoids develop and may regenerate green plantlets. Following colchicine treatment, fertility is restored and the double-haploid homozygous lines are obtained in about 20 months. The genetic heterogeneity of pollen grains gives rise to distinct DH lines with the following advantages for the breeder:

- The homozygosity is obtained in one step and is perfect because of exact genome duplication.
- Population size for efficient selection is the square root of a conventional F_2 for the same probability of selection of a given genotype, since there are no dominant recessive relationships.
- There is considerable economy in time and space in breeding work and genetic advances in the trait under investigation can be estimated in several years..

The research for improving the technique has focused on two main aspects:

- The physiological one—studying the culture medias for androgenesis and green plantlet regeneration and providing the best environmental conditions for growing as far as the physiological state of donor plants, from the understanding that a delicate balance between promoters and inhibitors is involved.
- The genotypic one—that studies the androgenetic capacity (a.c.), which is the capacity of a genotype to produce embryoids and green plantlets.

The a.c. is under genetic control, but is affected by plant growth and culturing conditions. Many desirable materials do not present a.c. and this is an important limitation to the method (Bajaj 1977; Gallais 1978; Foroughi-Wehr et al. 1982; Picard 1984, 1989; Picard et al. 1986, 1987, 1990; Heberle-Bors 1985; Hu 1985; Hu and Zeng 1985; and Moraes-Fernandes 1990).

In 1980, CNPT started a project on anther culture (Moraes-Fernandes and Picard 1983). More than 1000 double haploid lines have been obtained to date. About 400 genotypes from cultivars and segregating populations (F_1 to F_7) were tested and 40% of donor plants showed a.c., producing green plantlets; however,

only a few genotypes had a good a.c. The great majority of androgenetic plants came from a special project for adaptation to humid climates. The best genotypes developed embryoids from 4.2% of the anthers, with 65% of the embryoids producing green plantlets (Moraes-Fernandes et al. 1988c).

In 1984, CNPT began an experiment aimed at improving androgenetic capacity. Crosses were made involving androgenetic DH lines with good agronomic characteristics, adapted local cultivars, and F_1 populations of selected crosses. By culturing anthers coming from the F_1s of these crosses, DH lines of the second and third cycles were produced.

The best agronomic and androgenetic DH genotypes have been organized in a crossing block presenting variability for plant height, straw, and architecture; color, size, and pilosity (hairiness) of the leaf; color and size of the grain; color, size, and form of spike; glaucousness; resistance to the septoria and rust diseases; and tolerance to flooding and aluminum.

By using androgenetic DH lines in crosses made in 1987 to transfer *Aegilops squarrosa* genes of synthetic lines and subsequent anther cultures of the backcrossed F_1, the breeding work was speeded up considerably. DH lines derived from this experiment were multiplied in 1989 and the best are being evaluated in preliminary field trials in 1990. The accurate choice of donor plants in double, triple, or BC F_1 populations increases the probability of deriving good agronomic lines.

In 1988, eight cycles of culture were made from several breeding projects, including crosses, in which parents were not evaluated for a.c. Some good agronomic DH lines were obtained from several crosses and new genotypes for a.c. were identified. Since anther culture does not use all spikes, some F_2 seeds of the crosses were returned to breeders for normal field selection of segregating populations and thus both methods were used simultaneously.

DH lines derived from crosses made in 1984 were evaluated in preliminary trials in 1986. In regional trials in 1988, the best check, CEP 11, was outyielded by PF 843025 (19%), PF 853031 (15%), and PF 853083 (18%). In trials at Sul Brasileiro in 1989, the same DH lines were the highest yielders—18, 19, and 21% above the best check (Moreira 1989). The first wheat cultivar obtained by anther culture in Brazil may be released in 1991.

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Resumen

El mejoramiento de trigo en el sur de Brasil presenta muchos problemas a causa de varios factores bióticos y abióticos desfavorables que provocan importantes pérdidas de rendimiento. Las técnicas de la citogenética y la biotecnología son útiles para acelerar la labor de mejoramiento. En el Centro Nacional de Investigación de Trigo (CNPT), EMBRAPA, se efectuaron cruzamientos entre T. durum *(AABB, 2n = 28) y* Aegilops squarrosa *(DD, 2n = 14), seguidos por el recuento de cromosomas y el tratamiento con colchicina de híbridos producidos mediante el cultivo de embriones (ABD, 2n = 21). Se produjeron 11 líneas homocigóticas sintéticas hexaploides (AABBDD, 2n = 42) que proporcionan un método fácil y rápido para transferir en unos 12 meses buenas características de ambas especies progenitoras al nivel hexaploide. Las líneas haploides dobles (DH) pueden ser cosechadas en alrededor de 20 meses después del cultivo de anteras de las poblaciones F1. Se produjeron unas 1,000 líneas DH en el CNPT, que presentaron buena capacidad androgenética (a.c.). La gran mayoría de las líneas DH se derivaron de germoplasma proveniente de un proyecto fitotécnico encaminado a la adaptación a los climas húmedos. Este germoplasma también mostró buena capacidad androgenética. La elección precisa de plantas donantes por el fitomejorador en poblaciones F1 dobles, triples o retrocruzadas, provenientes de cruzamientos con líneas DH a.c., hexaploides sintéticos y variedades no androgenéticas, hacen posible derivar líneas homocigóticas buenas y variables, lo cual reduce el tiempo de mejoramiento, aun con ciertas limitaciones ya que las semillas F2 a.c. pueden ser devueltas a los fitomejoradores para seguir los procedimientos tradicionales. Tres de las mejores líneas DH provenientes de poblaciones F1 de 1984 (PF 843025, PF 853083 y PF 853031) se encuentran ahora en la verificación final y sus rendimientos son un 18, 19 y 21% superiores al de la mejor variedad testigo.*

CLOSING REMARKS

Summary of the Conference

R.A. Fischer, Director, Wheat Program, CIMMYT, El Batan, Mexico

This has been quite a unique meeting. More than 100 scientists from 24 countries across six continents with expertise in very different disciplines—ranging from economics to epidemiology and from modeling to molecular biology—have been brought together by a common interest in wheat, especially wheat in warmer areas.

Participants were able to listen to each other because all the sessions were plenary. Scientists from the three continents of the developing world have discovered common problems of wheat in the warmer areas. Information was shared on boron deficiency in Southeast Asia and in the Cerrados of Brazil, and on *Helminthosporium sativum* in the tarai of Nepal and the same poorly understood disease in Brazil's Paraná State.

Everyone saw wheat in the field in Paraná, which is representative of the 6 million hectares of wheat land double cropped with soybeans in this region of South America. This land shows serious sustainability problems, which are foremost on the research agenda of wheat scientists of the region and which provided much substance for valuable discussion at the meeting.

Since the 1987 meeting in Thailand, good progress was reported in most disciplines, even in economics where more rational national policies toward wheat in nontraditional areas have come to prevail in most countries. Some recent developments, for example, in the area of crop management in hot environments, in micronutrients, and in integrated aphid control management were new and exciting for most of the audience. Nevertheless, more than 60% of the wheat consumed in "tropical" countries is imported and marked progress in yields and production over the last 5 years has been limited to a few countries, e.g., Paraguay, Brazil, and Zambia.

Concern was often expressed especially about the weak state of our understanding regarding the principles underlying the adaptation of wheat varieties to warmer areas and their optimum crop management; pathology and entomology showed more soundly based progress, however. Unfortunately, little attention was given to technology transfer during the meeting.

Most presentations and discussion sessions called for more collaborative breeding with even greater targeting of the hot areas. A strong multidisciplinary approach was urged, especially the joining of physiology and breeding and of agronomy, pathology, and physiology. We were made aware of the relevance of new research tools in the areas of crop modeling and molecular biology while, at the same time, reminded of the power of a focused and protracted attack on a particular problem, e.g., the great success in improving scab resistance that wheat breeders in the lower Yangzte of China have had over the last 20 years. The fact that as many papers and discussions dealt with soil management (tillage, crop rotation, green manure, mycorrhizae) as with wheat breeding indicates the widespread feeling that possibilities exist to improve and stabilize yields through better agronomy—a discipline likely to receive greater and hopefully more analytical attention in the future.

Finally, several speakers recommended more attention be given to better and more quantitative evaluation of the productivity constraints and the impact of

research taking place under the umbrella of "nontraditional, warmer area wheat." Expressions of satisfaction and preferences for future activities, while genuine and valuable guides, need a more solid basis, which would undoubtedly be provided by such evaluations.

In 1984 I was fortunate enough to go to the first milestone conference on this subject in Mexico. I think the proceedings of our conference this week will be another milestone. The complete set of the three proceedings from the meetings in Mexico, Thailand (1987), and now Brazil will provide an excellent summary of the progress that has been and continues to be made over the course of this project sponsored by the United Nations Development Programme. I certainly feel optimistic on the basis of what was presented and seen this week that the next 3 years of the UNDP project should be very fruitful.

Field trip photos, Brazil and Paraguay

Participants, International Conference on Wheat for the Nontraditional, Warm Areas, Foz do Iguaçu, Brazil, July 29-August 3, 1990

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