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PROCEEDINGS OF A SYMPOSIUM ON THE

AGROMETEOROLOGY OF THE RICE CROP

World Meteorological Organization and
The International Rice Research Institute

The International Rice Research Institute

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PROCEEDINGS OF A SYMPOSIUM ON THE

AGROMETEOROLOGY OF THE RICE CROP

World Meteorological Organization and
The International Rice Research Institute

1980
THE INTERNATIONAL RICE RESEARCH INSTITUTE
Los Banos, Laguna, Philippines • P.O. Box 933, Manila, Philippines

Contents

Foreword

The World Food Conference (Rome, 1974) in its Resolution IV(6) recommended that the concerned national and international institutions intensify basic and applied research regarding:

(a) the impact of different ecological conditions, particularly climate, weather, and their variability, on agricultural production in various climatic zones and particularly in tropical and climatically marginal (e.g. semiarid and arid) land areas,

(b) the application of meteorological information and knowledge in planning agricultural research and land-use and management systems, including the development of alternative cropping strategies to suit different weather conditions so as to minimize the adverse effects of aberrant weather and encourage production patterns in tune with the climatic potential.

In response to this and other Resolutions of the World Food Conference, WMO has, since 1975, intensified its activities in the field of agrometeorology. These activities, directed toward the improvement of knowledge concerning the effects of weather and climate on agricultural production and the dissemination of this knowledge to meteorologists and agriculturists in Member countries, particularly those in the developing world, include the organization of technical conferences, training seminars, and symposia on various agrometeorological topics. This Symposium/Planning Meeting on the Agrometeorology of the Rice Crop was the third of a series of symposia on the agrometeorology of single crops; the two previous symposia dealt with the agrometeorology of the wheat and maize crops, respectively. In the organization of this meeting, we have been very fortunate in having the support of the International Rice Research Institute (IRRI) which readily agreed to host and to co-sponsor the event. It was, indeed, very appropriate that IRRI, the leading world rice center, was associated with this meeting and that the meeting was held in the heart of one of the most important rice-growing areas of the world.

Part I of this publication contains the papers presented during the first three days of the Symposium/Planning Meeting. These papers, presented by experts on the agrometeorological aspects of rice production, are in effect a summary of present knowledge on this subject. Part II is a report on the conclusions and recommendations of the various working groups which met during the two final days of the meeting to consider plans for further research into rice/weather relationships. Thus, these Proceedings are concerned with both past and proposed future activities in the agrometeorological aspects of rice research and as such are, I believe, of great potential value to workers in this field.

Many people contributed to the success of the Symposium/Planning Meeting. I wish to thank Dr. R. L. Kintanar, President of WMO and Permanent Representative of the Philippines with WMO and Dr. N. C. Brady, Director General of IRRI, both of whom kindly cooperated in arranging for the hosting of the meeting in the Philippines. We also thank Dr. W. Baier of Agriculture Canada and ex-President of WMO Commission for Agricultural Meteorology, who assisted in the program planning and acted as Technical Director. To these and to all others who helped to make this a most successful meeting, I have pleasure in expressing, on behalf of WMO, my sincere gratitude.

D.A. Davies

Foreword

Rice, which provides a third of the world's population with more than half their calories and nearly half their protein, is cultured in more diverse agrometeorologic conditions than any other food crop. Geographically, rice is grown in China at latitude 50°N, in central Sumatra on the equator, and in Australia and Uruguay at 35°S. It is grown below sea level in Kerala, India, and at elevations above 2,000 m in Kashmir and Nepal. It can be grown in upland, moderately submerged, and deep water conditions.

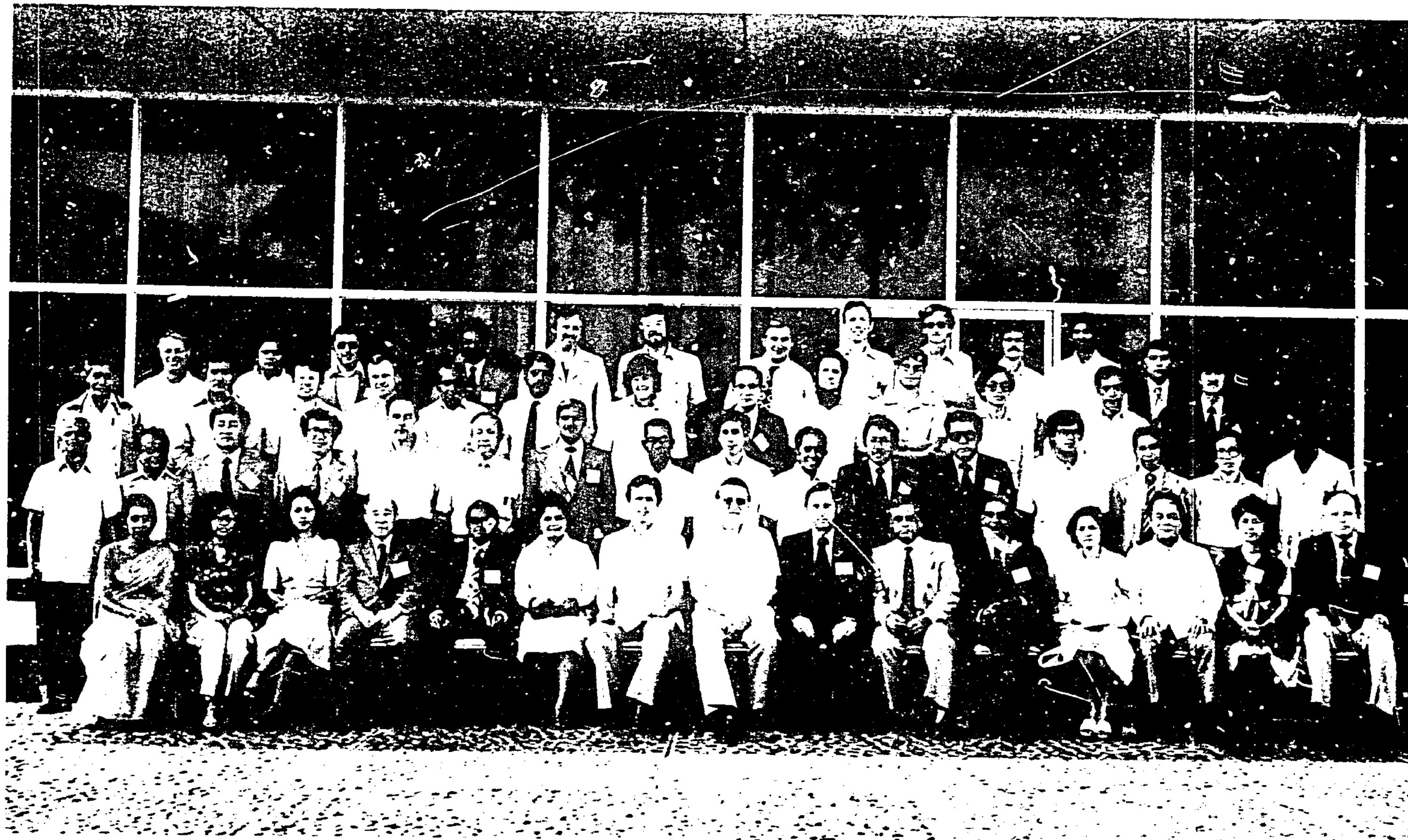
Scientists at IRRI have a long-standing interest in the response of rice to climatic factors. A 4-day (24-27 September) symposium on climate and rice followed the dedication of IRRI's phytotron in 1974. Many renowned biological and physical scientists from around the world participated. The published proceedings of that symposium form the basic reference on the interaction of climatic factors with rice growth, yield, and incidence of pests and diseases.

It was felt, however, that rice scientists needed a second forum in which to exchange new information. The symposium held 3-7 December 1979 at IRRI presented updated information on the agrometeorology of the rice crop. Working groups were formed to a) determine the status of weather records in rice-growing regions and plan their collection, analysis, and dissemination to users; b) determine essential meteorological variables to be monitored in rice-weather experiments and plan future experiments along this line; c) develop plans and priorities for rice-weather data analysis, such as mapping and crop modeling.

We are pleased that the World Meteorological Organization shares our common interest in these objectives and has extended its support in cosponsoring this symposium.

We wish to express our thanks to W. Baier and M.J. Connaughton for their assistance in organizing the symposium, and to the IRRI symposium committee made up of S.I. Bhuiyan, J.C. Flinn, H.E. Kauffman, R.A. Morris, and J.C. O'Toole (chairman).

N.C. Brady
Director general



SYMPOSIUM ON
AGROMETEOROLOGY OF THE RICE CROP • 3–7 DECEMBER 1979
LOS BAÑOS, LAGUNA, PHILIPPINES

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Opening remarks

It gives me great pleasure to welcome you to the WMO-IRRI Symposium/ Planning Meeting on the Agrometeorology of the Rice Crop. This is indeed a significant event in the history of WMO and IRRI since the two agencies, together with the national Meteorological Service of the Philippines and scientists from a number of countries, join in their efforts of evaluating current knowledge and planning future activities relevant to the agrometeorology of the rice crop. This meeting is part of a long-term plan by the Commission for Agricultural Meteorology to organize symposia dealing with the agrometeorology of single crops. Later on in this meeting I will provide you with background information on earlier events and our objectives for this Symposium/Planning meeting.

At the moment, I wish to introduce to you our honorary guests at the opening session. First, the Honorary President of the Symposium/Planning Meeting: Dr. R. L. Kintanar. Dr. Kintanar is the Director of the Philippines Meteorological Service and in this capacity the Permanent Representative of the Philippines with WMO. He is also the elected President of WMO. Mr. Krishnamurthy is the representative of the Secretary General of WMO. We are most grateful to Dr. Brady, Director General of IRRI, who has taken personal interest in our subject of discussion - i.e. agrometeorology of the rice crop - and who has actively supported this meeting by making available IRRI staff and facilities for this meeting.

I declare the Symposium/Planning Meeting open.

W. Baier

Welcome address

Mr. President, Ladies and Gentlemen,

I have pleasure in welcoming you on behalf of the Secretary-General of WMO to this WMO/IRRI Symposium on the Agrometeorology of the Rice Crop and to the Planning Meeting which will be held immediately after.

For the benefit of those who may not be familiar with the background to this symposium, or indeed with the activities of WMO in the field of agrometeorology, I should like to outline briefly the events leading up to the holding of this symposium. WMO, through its Commission for Agricultural Meteorology, has been involved in the weather aspects of agriculture for over 25 years. Most of the work carried out by the commission has been published as WMO Technical Notes. The titles of these technical notes indicate the diversity of the subjects studied — Weather and Animal Diseases, Frost Protection, Meteorology and Grain Storage, Wheat and Weather, Soil Moisture Problems in Agriculture, etc.

In addition, in cooperation with FAO and Unesco, WHO has organized agroclimatological surveys of various areas: semiarid and arid zones of the Near-East, semiarid areas of Africa South of Sahara Highlands of Eastern Africa, and the Andean Zone of Latin America. Yet another survey of Southeast Asia is under way. We are indeed fortunate to have with us this week Dr. Oldeman, the expert carrying out this survey, who I am sure will be pleased to provide further information to interested participants.

The activities of the Commission were given a further impetus by the Seventh Congress of WMO in 1975. Responding to the World Food Conference Resolutions, the Seventh Congress adopted an expanded program on agrometeorological activities in aid of food production. The objectives of the program included: (a) the strengthening of national agrometeorological services, especially in developing countries, (b) the provision of meteorological input to the FAO Global Information and Early Warning System on Food and Agriculture and (c) the organization of training seminars, symposia, technical conferences, etc.

Quite a number of important seminars, symposia and technical conferences were held in the last few years in various continents.

This symposium is the third in the series of symposia to be convened by WMO on the agrometeorology of single crops. The first on wheat was held in 1973 in the Federal Republic of Germany and the second on maize in the U.S.A. in 1976.

It is indeed fortunate that in arranging this symposium we have been able, through the wholehearted support of IRRI and the Government of the Philippines, to hold it in the heart of one of the big rice-growing areas of the world. WMO also wishes to express its gratitude to IRRI for its cooperation in cosponsoring this symposium.

The program schedule for the week is rather tight. I am sure that we shall all learn much during the coming five days.

In concluding, I should like to mention that the Seventh Session of CAgM, held in Sofia, Bulgaria in September this year, has authorized its president to take such action as he might find necessary after the WMO/IRRI Symposium and Planning Meeting. WMO and its Commission are therefore anxiously awaiting the recommendations from the Planning Meeting on the organization of rice experiments.

In conclusion, may I again, on behalf of the Secretary-General of WMO, bid you welcome to this symposium and wish you a fruitful and pleasant stay.

Thank you.

V. K. Krishnamurthy

Welcome address

We at the International Rice Research Institute are pleased to cosponsor this symposium with the World Meteorological Organization. My colleagues and I welcome you to IRRI and trust that your accommodations at the Institute are comfortable.

We meet here this morning, not because we are meteorologists or agriculturists but because the world needs more rice and because our research work must in some way help the world produce more rice.

Rice is the primary food for the world's low-income people. It is said that 90% of the truly low-income people of the world have rice as their primary or secondary food staple. Rice is certainly the primary food crop of Asia where the population pressures are greatest and where 90% of the world's rice is grown. It is an important crop in Africa and Latin America, and has the potential of becoming even more important in the future.

Rice yields are generally low in the tropics; national average yields range from 1.5 to 2.5 t/ha. This compares with a range of 4.5 to 6.0 t/ha for temperate zone countries. But potential yields in the tropics (13-15 t/ha) are not greatly different from the 15-17 t/ha potential for the temperate zone. Tropical region farmers are realizing only 10 to 20% of their potential yields while those in the temperate regions are obtaining 25 to 40% of their potential.

While management and socioeconomic factors play major roles in accounting for these differences, the environment and specifically climatological and meteorological factors are major determinants of farm yields. For example, the amount and timing of water supply, which in the tropics is largely beyond human control, are major factors in limiting rice yields and production.

Rice is grown under extremes of water conditions. It grows as a dryland crop, under irrigated conditions where the water is well controlled, and under rainfed conditions where the floodwaters may be either shallow or as much as 5 m deep. In South and Southeast Asia about 8% of the rice grow under dryland or upland conditions; about 10% are in deepwater areas where floating type rices prevail; about 25-30% have good irrigation; the remainder grow in rainfed areas, in 30-35% of which water would be relatively shallow and in 15-20%, up to 1 m deep each year.

Let me illustrate the influence of climate and water control on rice by referring to changes in rice yields in two distinctly different climatic regions of India. In the Punjab area of northwestern India rice yields during the last 15 years actually went up more rapidly than did those of wheat. But in eastern India, where much more rice is grown, yields remained relatively the same during the 15-year period.

Differences in climate and in turn water regimes largely account for these yield differences. In the drier but well-irrigated areas of northwest India where high solar radiation prevails, new varieties have responded dramatically to fertilizer inputs and marked yield increases have resulted. But in eastern India, generally more humid conditions prevail. Solar radiation is lower, insect and disease pressures are higher, and during the monsoon response to fertilizer is limited. Furthermore, high rainfall dictates deep flooded conditions which are not conducive to the production of modern high yielding varieties. Climate and water abundance and control are thus seen to be primary factors in setting limits on rice production.

While the influence of climatic variables is easily recognized in comparing these two regions of India, generally there is all too little information on climatic and meteorological factors influencing rice production. There is a need for descriptive information about the climate in areas where rice is grown and especially about the water regimes which result. Also we know too little about the response of the rice plant to changes in the climatic environment. To gain such knowledge, we need interaction among climatologists, meteorologists, and biologists such as are represented here today.

The objective of this symposium is twofold: to review what is known about the agrometeorology of the rice crop and to determine priorities for research on this subject. We wish you well in achieving this objective.

N.C. Brady

I. Climatic aspects of rice production (review)

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Climatic constraints to rice production in the Philippines

Ed. B. Pantastico and A. C. Cardenas

Climate as a constraint to rice production in the Philippines is discussed. Typhoons, floods, and drought caused 80% of the total rice losses in the past 10 years. The rice-growing areas of the country are classified as very stable, stable, less stable, and unstable production areas. Crop production strategies to minimize the climatic hazards in less stable and unstable production areas are discussed.

The Philippines, a typical tropical rain forest (Richards 1972), has an annual mean rainfall of 253 cm (272 cm in Luzon, 239 cm in the Visayas, and 235 cm in Mindanao). The annual average relative humidity is 82%. The daily high temperatures fluctuate from 22.8°C in February to 31.3°C in June (annual mean, 27°C).

The country is influenced by monsoon currents, tropical cyclones, and the intertropical convergence zone which divides the year into well-defined wet and dry seasons. The production of annual crops is essentially determined by the wet season. The climate is also influenced by topography and, to some extent, by fronts and easterly waves. Many areas have rain from May to November, the peak amounts falling in August to September. During the dry months (Feb-Apr) rainfall is deficient and some places experience drought.

The three major hazards to rice production are typhoons (i.e. tropical cyclones involving tropical depressions, storms, and typhoons) and floods, drought, and pests (Table 1 and Fig. 1). From 1968 to 1977 annual losses in the total rice production due to these factors reached 9%. The combined effects of typhoons, floods, and droughts accounted for almost 80% of these losses. Typhoons and floods caused major losses in 8 years; drought, losses in 3 years; and pests, losses in another 3. Furthermore, in years with great losses from drought, there was also damage from typhoons and floods.

Table 1. Average quantity, value, and percentage losses of rice production in the Philippines, 1968-77.[a]

Factor	Quantity (hundred t)	Value (million US$)	Total production (%)	Total loss (%)
Av annual production	5,297	3,601.96		
Av annual losses	498	44.45		
Total loss			.02	-
Typhoons and floods	264	23.97	4.98	55.23
Drought	115	11.49	2.17	24.06
Pests (insects, diseases, rats)	98	8.89	1.85	20.50
Others	1	.07	<.01	.20

[a]Bureau of Agricultural Economics, 1978.

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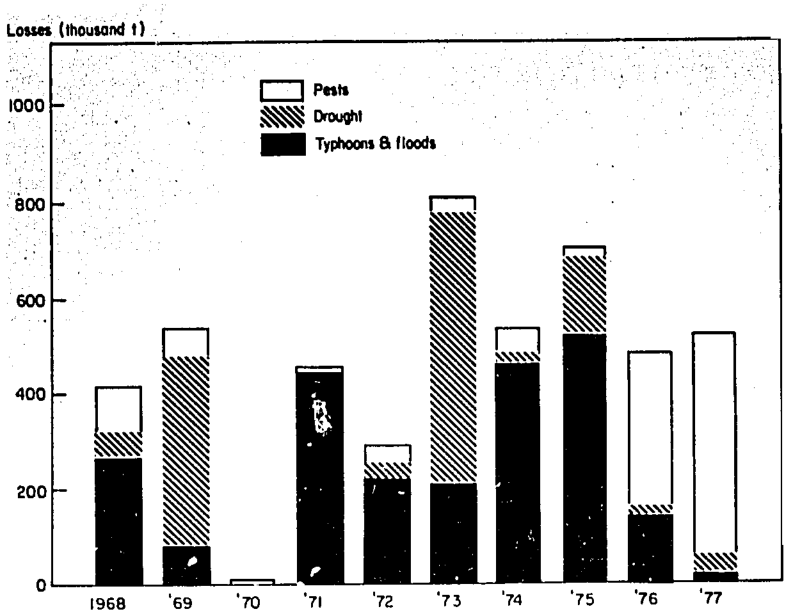

1. Yearly losses in Philippine rice production, 1968–77.

TYPHOONS AND FLOODS

From 1968 to 1975, the value of rough rice lost to typhoons, floods, and droughts reached US $64.5 million. About 295,000 t (5.4% of total production) were destroyed by typhoons and floods and 145,000 t (2.6%) were lost to drought (BAECON 1968-77). Only 0.74% was lost to other causes, including pests (Baradas 1978).

An average of about 11 typhoons per year pass through the Philippines. Table 2 shows the frequency with which typhoons affect various regions.

The 90-year accumulated data on the monthly occurrence of typhoons show that 50% pass over the Philippines during July, August, and September, and 25% occur in October and November (Table 3).

Because of the heavy rainfall during the passage of typhoons and the intensification of the monsoons, big rivers in low-lying areas overflow and cause floods that may persist from 1 to 5 days. These floods occur almost yearly. They wash out the rice plants and damage the crop that is submerged in muddy water (Table 4).

There is an urgent need to consider the climate when developing strategies to increase and stabilize rice production.

POTENTIAL DROUGHT AREAS

Table 5 shows rice yields in dry areas that have light soils. Drought damage could be aggravated by the presence of light soils in rainfed areas. The Ilocos region and some parts of Central Luzon and Cagayan are the most likely places to experience drought, especially from February to April. Losses in dryland rice production may not be great during these months but losses during September to November as a result of early stoppage of rain could be serious. Intermittent rain during May, June, and July could cause seedling losses.

CLASSIFICATION OF RICE PRODUCTION AREAS

Among the rice-growing countries, climate variability partly explains the observed variations in yield. The environmental requirements and the quantitative description of the climate (preferably given in terms of probabilities of occurrence) must be known in order to identify appropriate rice-growing areas.

In broad terms, the rice production areas of the Philippines can be categorized as: very stable, stable, less stable, and unstable.

This classification is offered to dramatize the risk involved in rice

Table 2. Typhoon frequency and places affected (1882-1972) in the Philippines.

Frequency	Region	Province or area
Very high (31-40%)	I Ilocos	Ilocos Norte
	II Cagayan Valley	Batanes, Cagayan, Kalinga Apayao, Nueva Vizcaya, Quirino, Ifugao, Isabela
	IV Southern Tagalog	Northern Aurora
	V Bicol	Legaspi, Masbate
High (21-30%)	VIII Southeast Visayas	Samar
	I Ilocos	Ilocos Sur
	IV Southern Tagalog	Northern Mindanao, Rizal, Laguna, Southern Aurora, Southern Quezon
	V Bicol	Camarines Norte, Camarines Sur
	VII Central Visayas	Romblon
	VIII Eastern Visayas	Northern Leyte
Medium (11-20%)	I Ilocos	Baguio, Pangasinan
	III Central Luzon	Nueva Ecija, Zambales, Bulacan, Pampanga, Tarlac
	IV Southern Tagalog	Metro Manila, Southern Mindanao, Northern Palawan
	V Western Visayas	Southern Iloilo, Negros Occidental
	VII Central Visayas	Cebu, Bohol
	X Northern Mindanao	Surigao del Norte
Low (0-10%)	III Central Luzon	Bataan, Southern Zambales
	V Southern Tagalog	Batangas, Southern Palawan
	VI Western Visayas	Northern Iloilo
	IX Western Mindanao	Zamboanga, Sulu
	X Northern Mindanao	Cagayan de Oro, Agusan (North & South), Misamis, Bukidnon
	XI Southern Mindanao	Davao, South Cotabato, Surigao del Sur
	XII Central Mindanao	Lanao, North Cotabato, Sultan Kudarat

Table 3. Monthly occurrence of typhoons (1882-1972) in the Philippines.[a]

Frequency (%)	Month	Area
18	Aug	Northern Ilocos, Cagayan Valley
17	Jul	Northern Ilocos, Cagayan Valley
15	Sep	Southern Ilocos, Southern Cagayan
13	Oct	Northern Samar, Masbate, Romblon, Coron, Palawan
12	Nov	Southern Samar, Northern Leyte, Northern Aklan
9	Jun	Eastern and Western Samar, Southern Masbate, Southern Mindoro
7	Dec	Central Leyte, Northern Cebu, Capiz, Northern Iloilo, Southern Iloilo, Southern Aklan
4	May	Albay, Camarines Sur, Southern Batangas, Southern Quezon, Marinduque
3	Jan	Surigao del Norte, Bohol, Southern Negros, Southern Cebu, Southern Samar, Aklan, Coron, Central Palawan
1	Mar	Surigao, Southern Leyte, Central Cebu, Central Negros Occidental, Northern Palawan

[a]Source: PAGASA, 1970, Manila, Philippines.

Table 4. Yield reduction in rice submerged at selected growth stages in the Philippines (after Caoili, n.d.).

Growth stage	Yield reduction (%) at different days of submergence			
	1-2	3-4	5-7	7 & above
Panicle formation partly inundated	20	50	85	90-100
Panicle formation completely inundated	70	30	85	90-100
Heading	30	80	90	90-100
Ripening	5	20	30	30

Table 5. Yield of first, second, and third crops in dry areas having light soils in the Philippines.

Dry area	Rainfall type[a]	Crop yield (t/ha)				
		First	Second	Third		Total
San Fernando, La Union	3.3	Rice 3.3	Rice 4.9	Sorghum	3.3	11.5
Echague, Isabela	3.3	Rice 2.4	Rice 1.7	Soybean	0.7	4.8
				Cowpea	0.3	4.4
				Sweet potato	2.4	10.6
Sta. Maria, Bulacan	3.3	Rice 2.9	Rice 2.4	Corn	1.5	6.8
				Sorghum	1.8	7.1
				Soybean	1.0	6.3
				Peanut	1.9	7.2
				Sweet potato	3.6	8.9
Sta. Maria, Pangasinan	3.4	Rice 1.5	Rice 3.7	Corn	4.7	9.9
				Sorghum	6.7	11.9
				Mungo	0.6	5.8

[a]3.3 = 5-6 DM (dry months) and 5-6 WM (wet months); 3.4 = 5.6 DM and 3.4 WM.

production. It is hoped that when the areas are delineated, the categories will provide a base for sound policy in planning and implementing rice production.

Very stable production areas

Very stable production areas are seldom visited by typhoons and have minimum climatic hazards. Annual rainfall is evenly distributed. Soils have good tilth. Many rice production areas in Mindanao, like Agusan, Davao, Cotabato, and Zamboanga fall in this category.

Stable production areas

The present rice bowls of the country -- Central Luzon and Western Visayas, particularly southern and central Iloilo -- may be considered stable production areas. They have a distinct rainfall pattern and 11-20% typhoon frequency. Agricultural production planning has a high degree of certainty. Soils generally retain water well.

Less stable production areas

Among the less stable production areas are those with erratic rainfall either during the start or the tail end of the wet season or during both. Typhoons are frequent (21-30%). Seedlings often die because of minimal rains after the initial heavy rains. Harvest failures result from typhoons or early drought during the rice's later growth stages. Such failures can be aggravated by light-textured soils. Part of the southern Tagalog region, Ilocos, Bicol, and the Visayas are in this category.

Unstable production areas

Ilocos Norte, Batanes, Cagayan, Aurora, the southern Bicol provinces, and Samar in the Visayas are probably in the group of unstable production areas. Agricultural planning is difficult. Typhoon frequency is very high (31-40%), and soil may erode in rolling areas. Siltation may occur in lowland river basins and cause early drought during the dry season.

PRODUCTION STRATEGIES IN DROUGHT AND TYPHOON-BELT AREAS

The potential for increasing rice yields in the tropics is greatly determined by the extent to which the policy-makers, scientists, change agents, and farmers rationally harness the tropical climate. Existing efforts toward these ends may be classified arbitrarily either as remedial or preventive, the former being exemplified by the post-typhoon rehabilitation programs of the government.

Cloud-seeding may become man's most sophisticated undertaking to moderate the destructiveness of typhoons. Research and development of this technology has been going on in typhoon areas worldwide, including the Philippines.

Reforestation is an accepted program to restore the water retention capability of watershed areas, and provides an effective natural control device against cyclonic floods.

There are recommended rice production practices in the less stable and unstable production areas. O'Toole and Chang (1978) stress the use of early-maturing rice varieties and Zandstra (1978) and Drilon and Pantastico (1979) proposed cropping systems to overcome failure and improve farmers' rice production.

A crop management alternative to meet the continuous threat from typhoons and floods is to *plant more during the typhoon-free dry season.* High intensity solar radiation during the dry season promotes greater photosynthesis. However, the unavailability of water at critical stages of crop growth poses a serious constraint. The construction of farm ponds and community level water catchments could solve this constraint (Baradas 1978). Therefore, research needs to develop methodologies that will enhance a production system's capability to cope with typhoons. The following are possible strategies (PCARR 1979):

1. Ratooning for shorter growing periods
2. Improving and planting of
   - wind-tolerant or lodging-resistant crops and varieties
   - nonshattering varieties
   - waterlogging-resistant varieties
3. Improving seed dormancy characteristics to control germination time
4. Modifying seedling management, i.e. prolonged periods or raising seedlings in seedbeds
5. Designing and developing simple implements for rapid harvesting and postharvest handling under typhoon conditions
6. Establishing windbreaks in strategic areas
7. Developing methods to conserve rainwater so that the planting period can be extended
8. Modifying planting schedules, and
9. Providing crop insurance in the form of readily available replacement seedlings.

These suggestions, however, are far from complete. There is an urgent need to concentrate on stabilizing rice production if we are to sustain self-sufficiency and the export of rice. Typhoons increase the risk to both subsistence and business-oriented farming. They influence the farmer's willingness to adopt improved technology, especially that which requires relatively higher inputs. In marginally productive rainfed areas within typhoon belts where only a single crop of rice is usually planted, typhoons compound low farm productivity.

CONCLUSION

Typhoons, floods, and drought cause yield losses every year in the Philippines. A proposal is offered to group the rice production areas of the country into the categories very stable, stable, less stable, and unstable. When these areas are fully defined and delineated, we will be in a better position to plan rice production strategies.

Although there are recommended strategies to develop cropping systems in less stable and unstable rice-growing areas, the combination and integration of these various recommendations must be tested. Environmental research to describe climate, soil, and economic factors must be linked to rice production systems. Researchers and farmers must join efforts to understand the crop-climate relationship and formulate viable production technologies. And finally, the agricultural sector should consider a policy decision on where to locate rice production areas to assure a sustained food supply for both the Philippines and our Asian neighbors.

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Meteorological aspects of rice production in Central and South America — current and future

F. S. da Mota

Central and South America have a great potential to increase rice production both in dryland and irrigated crops.

Drought is the major constraint to rice production in Latin America, but cold injury is also a problem.

Regional climatic classifications based on daily soil-water balance models are not available for Latin America. However, where adequate rainfall data are available, meteorologically homogenous and low-rainfall areas can be identified.

A comparison between rice production areas in Latin America and the mean temperature in January show no rice production in some areas where the temperature is below 20°C.

The general picture of radiation regimes in Brazil is given.

In order to appraise the real contribution of each meteorological element, it might be advantageous to develop regional models from available historical weather and yield data and to set up an international experiment to gather special data for a more detailed analysis.

Rice is the most important single food crop in the world today. Its importance will increase because population growth is far more rapid in rice consuming areas than in nonrice areas. The future expansion of the world's rice land will probably be in dryland areas because in traditional rice growing regions most of the land suited to irrigated paddy culture is already in use. The expansion of dryland rice areas is more feasible in some parts of Africa, the *cerrado savanna* area in central west Brazil, and the Amazon Basin than anywhere in Asia.

About 5% of the world's rice is grown on 6.5 million ha in Latin America. The average yield is 1.7 t/ha. Brown (1969) reported that about 65% of Latin American rice is grown under dryland conditions; Sanchez (1972) estimated 75% (Table 1). Brazil, the largest country in Latin America, has the largest dryland rice area, about 3.5 million ha with an average yield of 1.3 t/ha. Average rice yields of Colombia (4.2 t/ha), Uruguay and Peru (3.9 t/ha), and Argentina (3.9 t/ha) are significantly higher because these countries primarily grow irrigated rice.

Brazil has 1.7 million ha of wetland rice. However, 50 million ha of wetlard soils can be *used* for irrigated crops, including rice. A great percentage of this wetland is below 14°S lat. where the climate suggests the possibility of growing two crops of rice in one year (Fig. 1). Yields from irrigated rice are increasing (Fig. 2). The present policy in Brazil is to increase the irrigated rice area for greater yield stability.

This paper intends to give a general picture of the macro-climatic conditions important for rice production in Latin America.

RICE PRODUCTION IN LATIN AMERICA

Most dryland rice in Brazil is grown on small and medium-sized farms with somewhat rolling topography. The average yields range from 1.2 to 1.5 t/ha. About 15% of Brazil's total rice is grown under dryland shifting cultivation and in mixed cropping patterns

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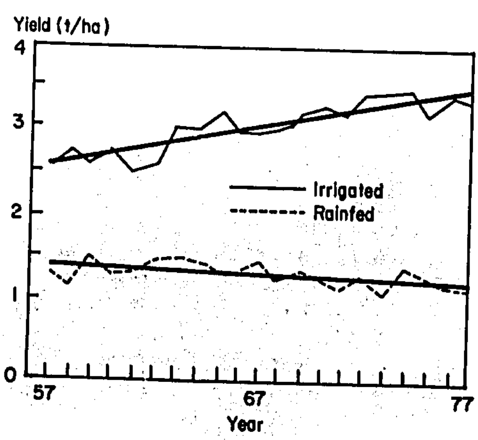
Table 1. Total rice area in South and Central America, percentage of dryland rice in key countries, and average yields in 1975. Adapted from data presented by Scobie and Posada (1977) and De Datta (1975).

Country	Total rice area (thousand ha)	Dryland rice area (% of total)	Av yield (t/ha)
Argentina	103	-	3.9
Bolivia	45	-	1.7
Brazil	5200	77	1.3
Chile	24	-	3.2
Colombia	387	65	4.2
Ecuador	128	63	2.4
Guyana	122	55	2.5
Paraguay	20	-	2.0
Perú	117	21	3.9
Surinam	40	-	3.3
Uruguay	45	-	3.9
Venezuela	106	80	3.8
South America	6337	70	1.7
Costa Rica	55	-	2.6
El Salvador	12	-	2.8
Guatemala	22	-	2.9
Honduras	12	-	2.2
Nicaragua	29	-	3.1
Panamá	115	95	1.5
Central America	245	90	-

with corn, beans, squash, bananas, and cassava in the northern and northeastern regions (Table 2). Rice culture is semimechanized, and rice is often the first crop on newly cleared savanna lands in the central-west *cerrado* *savanna* areas. This 3.7 million ha is probably the world's largest continuous dryland rice-growing area and produces 70% of Brazil's rice.

Colombia, Guyana, Panama, Ecuador, Peru, and Venezuela are other important dryland rice-growing countries. About 21% of Peru's rice crop comes from dryland shifting cultivation in the Amazon basin (Sanchez 1972, Cha 1967). In this vast ecological region, which covers half of Peru's land surface and extends deeply into Brazil, Bolivia, Colombia,

1. Dotted areas indicate Brazilian regions suitable for irrigated rice.



2. Rice yields in Brazil.

Table 2. Area planted and production of dryland and wetland rice in Brazil, 1970 (from Souza 1973).

State[a]	Production (thousand t)	Area planted (thousand ha)
Rio Grande do Sul (W)	1543	431
Goiás (D)	1217	1098
Minas Gerais (D)	1165	877
São Paulo (D)	1053	703
Maranhão (D)	675	553
Mato Grosso (D)	616	321
Paraná (D)	590	432
Santa Catarina (W)	214	86
Pará (D)	73	75
Bahia (D,W)	58	39
Total	7204	4615

[a]W = wetland culture, D = dryland culture.

and Ecuador (Sanchez and Nureña 1972), upland rice is grown on both flat and sloping areas. This cultural system involves cutting and burning the mature secondary forest from July to September and then dibbling seeds into holes made with a *tacarpo*, a pointed stick (Sanchez and Nureña 1972). Grain yields range from 0.5 to 0.7 t/ha.

The yields from dryland rice in Latin America can be increased by using improved varieties and cultural practices that suit the soil, climate, and social conditions. High yields are possible. Yields of 7.2 t/ha have been recorded in Peru (Kawano et al 1972). But the area planted to dryland rice is so large that even a small increase would substantially influence total rice production.

CLIMATIC REQUIREMENTS OF RICE

Rainfall

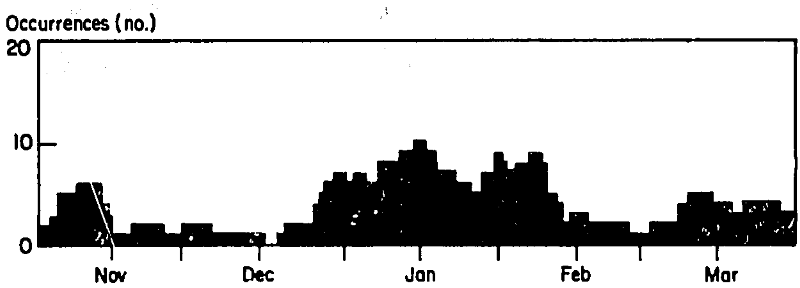
Brown (1969) reported that 1,000 mm of annual rainfall, with 200 mm monthly rainfall during the growing season, is adequate for growing dryland rice in Latin America.

Brazil has a distinct rainy season that begins in October and ends in April. The average annual rainfall varies from 1,300 to 1,800 mm; 70 to 80% falls during the dryland rice growing season. The rainfall tapers off in February, leading to an ideal harvesting period that results in milled rice of better quality.

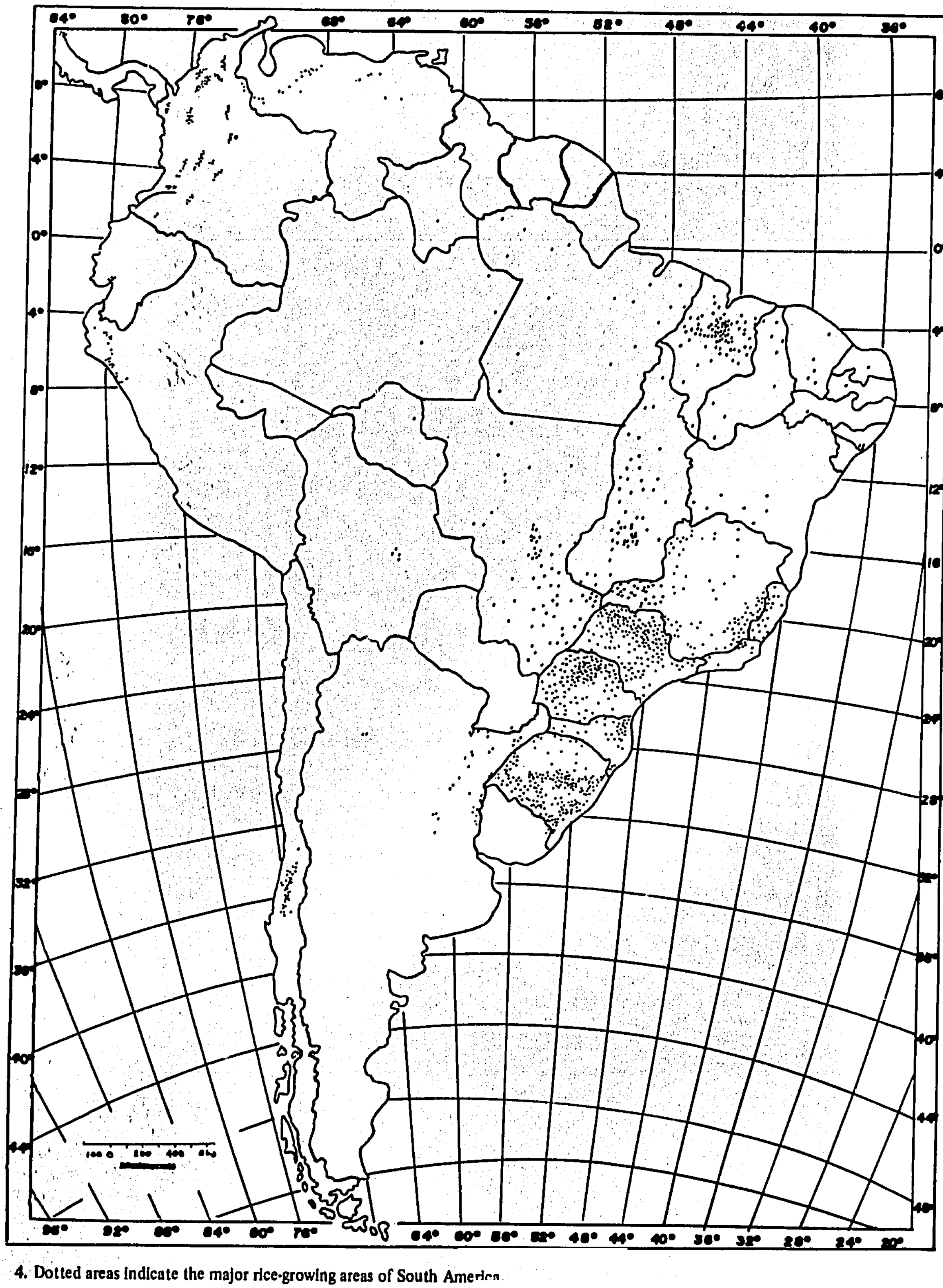
Rainfall in most of Peru's Amazon basin ranges from 2,000 to 4,000 mm annually (Sanchez 1972). Kawano et al (1972) reported yields of more than 4 t/ha, with rainfall averaging 200 mm/month during the growing season.

Daily rainfall is more critical than monthly or annual rainfall. A rainfall of 100 mm/month, distributed evenly, is preferable to 200 mm/month, which all falls in 2 or 3 days.

Understanding rainfall patterns and distribution in relation to rice physiology and soil conditions is a prerequisite for successful crop planning.



3. Histogram of the "veranico" or maximum dry spell during the wet season in Brasilia, Brazil (from Wolf 1977).



4. Dotted areas indicate the major rice-growing areas of South America.

Rainfall data are generally available. In the Brasilia area, the wet season is from November to March. Daily rainfall records for 42 years (Wolf 1977) revealed an 8% chance that in any year the longest dry spell during the wet season (*veranico*) will be limited to 8 days or less, a 50% chance that it will be 14 days or more, and a 15% chance that it will exceed 3 weeks. Figure 3 shows the histogram of veranico for Brasilia. Thus, drought tolerance must be incorporated into high-yielding dryland varieties for use in Brasilia.

Regional climatic classifications based on daily soil-water balance models indicate agricultural potentials but such studies are not now available for Latin America. Until they become available, we must rely on macroclimatic analysis. Where adequate rainfall data are available, meteorologically homogeneous and low rainfall areas can be identified using criteria from the working group on the establishment of Southeast Asian cropping systems test sites at the International Rice Research Institute, Los Baños, Philippines (Robertson 1975).

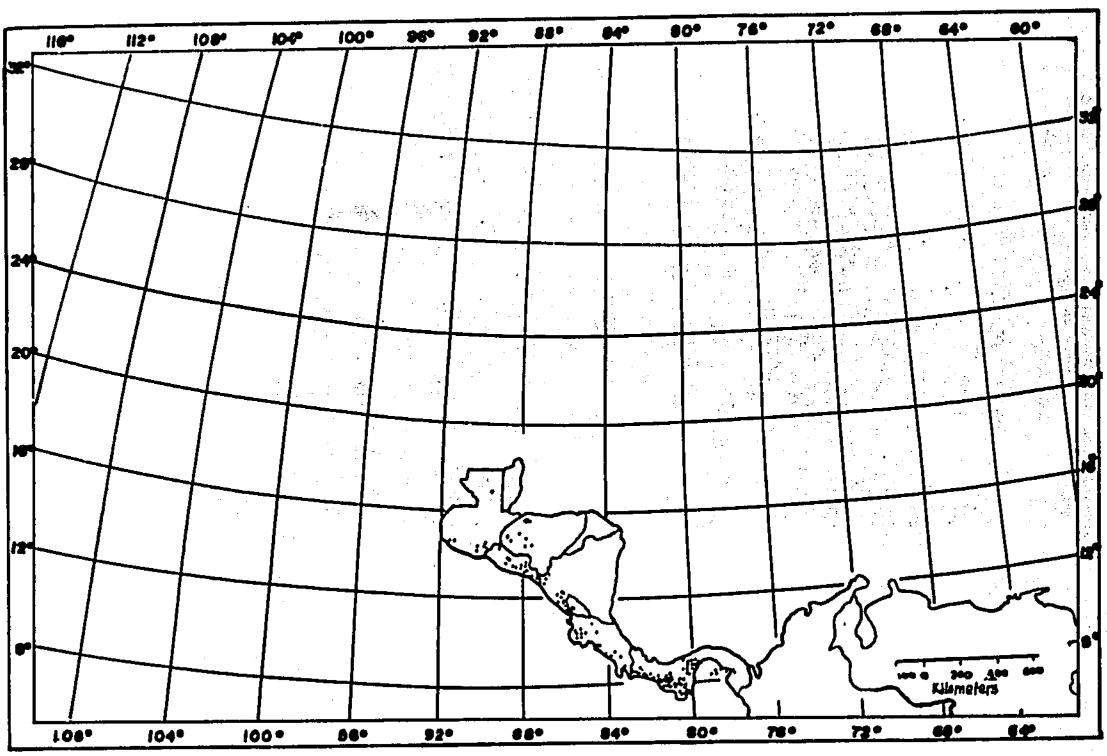
Temperature

Rice is seldom produced commercially in areas where average temperatures drop below 21°C. Many researchers have reported on temperature in relation to rice production (Sircar 1948, Van Royen 1954, Wellhausen 1957, Grist 1959, Nuttonson 1965, Papadakis 1970). Robertson (1975), in his survey of world climatic conditions in rice-producing areas, shows that the mean maximum daily temperature during the life cycle of the rice crop varies from 30.3° to 35.6°C in the warmest region (Ghana) and from 9.3°C (30 day before sowing) to 25.3°C (at heading) in the coldest region (Hokkaido, Japan).

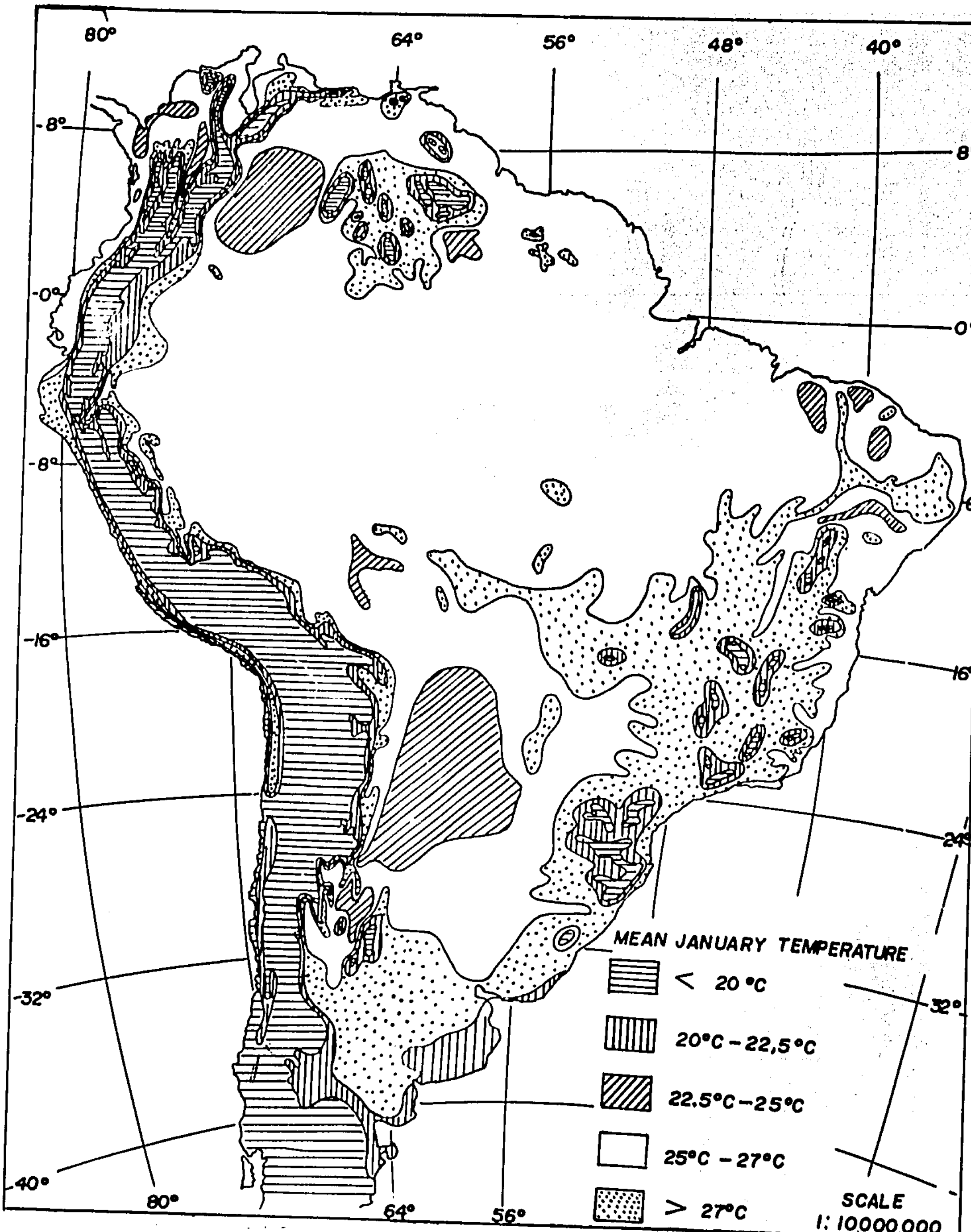
A comparison between rice production areas in Latin America (Fig. 4,5) and the mean temperatures in January (Fig. 6) show no rice production in areas where the temperature is below 20°C.

Sunlight

According to Stansel (1975) rice variability in different parts of the world is the result of diverse environments and



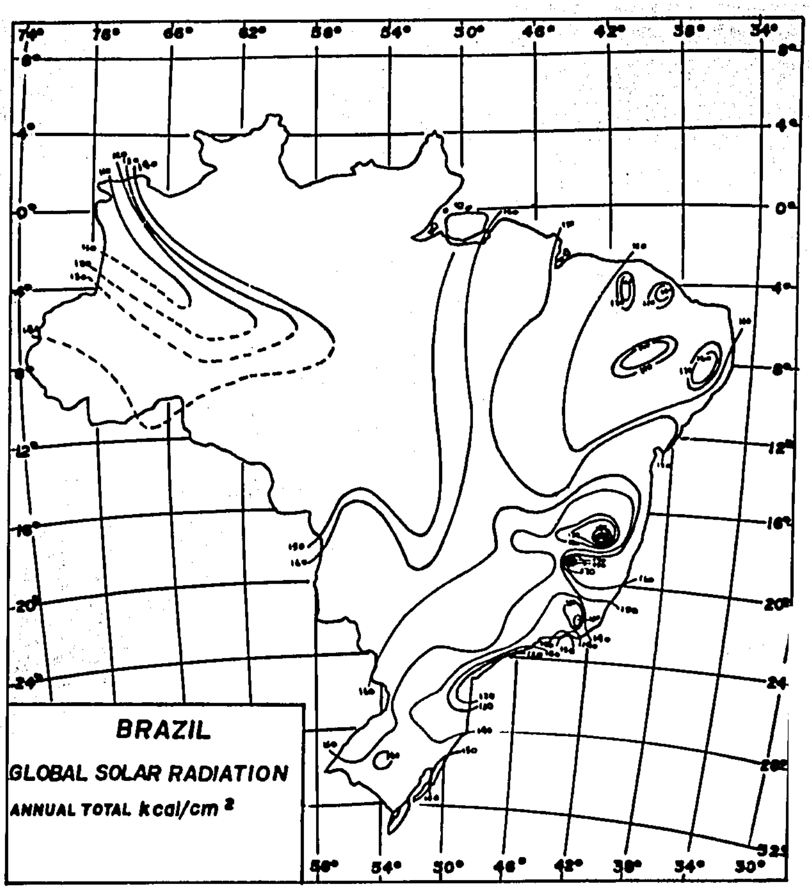
5. Dotted areas indicate the major rice-growing areas of Central America.



6. Mean January temperature in South America (adapted from Hoffmann 1975).

the selective forces of the cultural practices in use. Environment plays a leading role in determining growth, development, and yield.

Low yields occur when rainfall is higher than normal during the growing season. Rice plants grow tall and lodge severely, panicles have a large number of blank florets, and nitrogen fertilizer is less effective. The highest yields occur in years with lower rainfall and greater sunlight. The plants are shorter,



7. Global solar radiation, annual totals (from Mota et al 1976).

lodge less, have fewer blank florets, and respond to nitrogen fertilizer. The highest potential for production on a one-crop basis occurs in areas where levels of available sunshine are high at critical stages and moisture is available. However, the sun's energy can be used only when other constraints have been controlled. Plentiful sunshine will not help yields if the crops are seriously affected by water and nutrient stresses, pests, and diseases. Figure / gives the general picture of radiation regimes in Brazil.

MACROCLIMATIC ELEMENTS IMPORTANT FOR RICE IN SOUTH AND CENTRAL AMERICA

According to Robertson (1975) the production of rice is limited by the following climatic constraints:

1. Low temperature limiting the duration of the growing season, and the rate of growth and development;
2. High temperature during the growing season causing a thermal stress;
3. Insufficient water;
4. Excessive flooding;
5. Low global solar radiation limiting the rate and amount of photosynthesis; and
6. Long photoperiod limiting the choice of suitable varieties.

One or more of these constraints limit yields in several of the areas that produce or can produce rice in Latin America.

CONCLUSION

Many bioclimatic elements affect the growth and final yield of the rice crop. In order to appraise the real contribution of each of these elements, it might be advantageous to develop regional models from available historical weather and yield data and to set up an international experiment to gather special data for such an analysis as proposed by Robertson (1973). The maps presented in this paper may be useful to select sites for such experiments in Latin America.

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Meteorological aspects of rice production in India

P. S. Sreenivasan

A study of rice spread and yield in India juxtaposed with rainfall amount and distribution revealed that rice is extensively cultivated in regions receiving an average rainfall of more than 250 mm/month for at least 3 consecutive months. The potential for higher rice yields under irrigation is maximum in the meteorological subdivisions of interior Karnataka.

The differential rice spread and production suggest that the meteorological aspects of rice within a subdivision must be studied in depth.

Regression formulas to forecast rice yields from weather parameters for meteorological subdivisions are presented in the appendix.

Rice is India's most important cereal in area and production. *Oryza sativa* (indica), which originated under the varied climate of India, is a tall plant with a large number of leaves, tillers profusely, and has photoperiod sensitivity that makes the period of maturity variable, depending on the time of planting.

The India Meteorological Department (IMD) has investigated on a macroscale the meteorological aspects of Indian rice production. The National Commission on Agriculture (NCA) has made a quinquennial projection of rice production based on crop potential in various agroclimatic regions.

AREA AND YIELD

The relative area and yield indices for rice-growing districts of India were worked out by employing the average area and yield for 1970-72 (Directorate of Economics and Statistics 1973):

$$\text{Relative spread index} = \frac{\text{Area of rice as a fraction of cultivated area in the district}}{\text{Area of rice as a fraction of total cultivated area in the country}} \times 100$$

$$\text{Relative yield index} = \frac{\text{Mean yield for rice in the district}}{\text{Mean all India yield}} \times 100$$

Figure 1 gives the relative area and yield indices for each district. Contiguous districts with negligible area under rice are delineated by thick lines. The map suggests that rice cultivation extends to a) the west coast consisting of the meteorological subdivisions Kerala, coastal Karnataka, and Konkan (including Goa); b) Tamil Nadu, coastal Andhra Pradesh, Orissa on the east coast; c) Bengal, Assam, and Meghalaya in the east; d) the Kashmir valley; e) the foothills of the Himalayas, consisting of West Uttar Pradesh, East Uttar Pradesh, and the Bihar Plains; and f) mainly East Madhya Pradesh and Bihar Plateau in Central India. Areas with high yield but low rainfall include a) the south and north interior Karnataka, Rayalaseema and Telangana; and b) North India made up of Punjab, Haryana, and the western portions of West Uttar Pradesh. Water seems to be the limiting factor in bringing more areas under rice production.

Rice yield potential

Although the yield ratios between irrigated and unirrigated areas would bring out the relative performance of rice in the various states, production for irrigated and rainfed crops has not been recorded separately. Assuming that the yields of rainfed and irrigated rice

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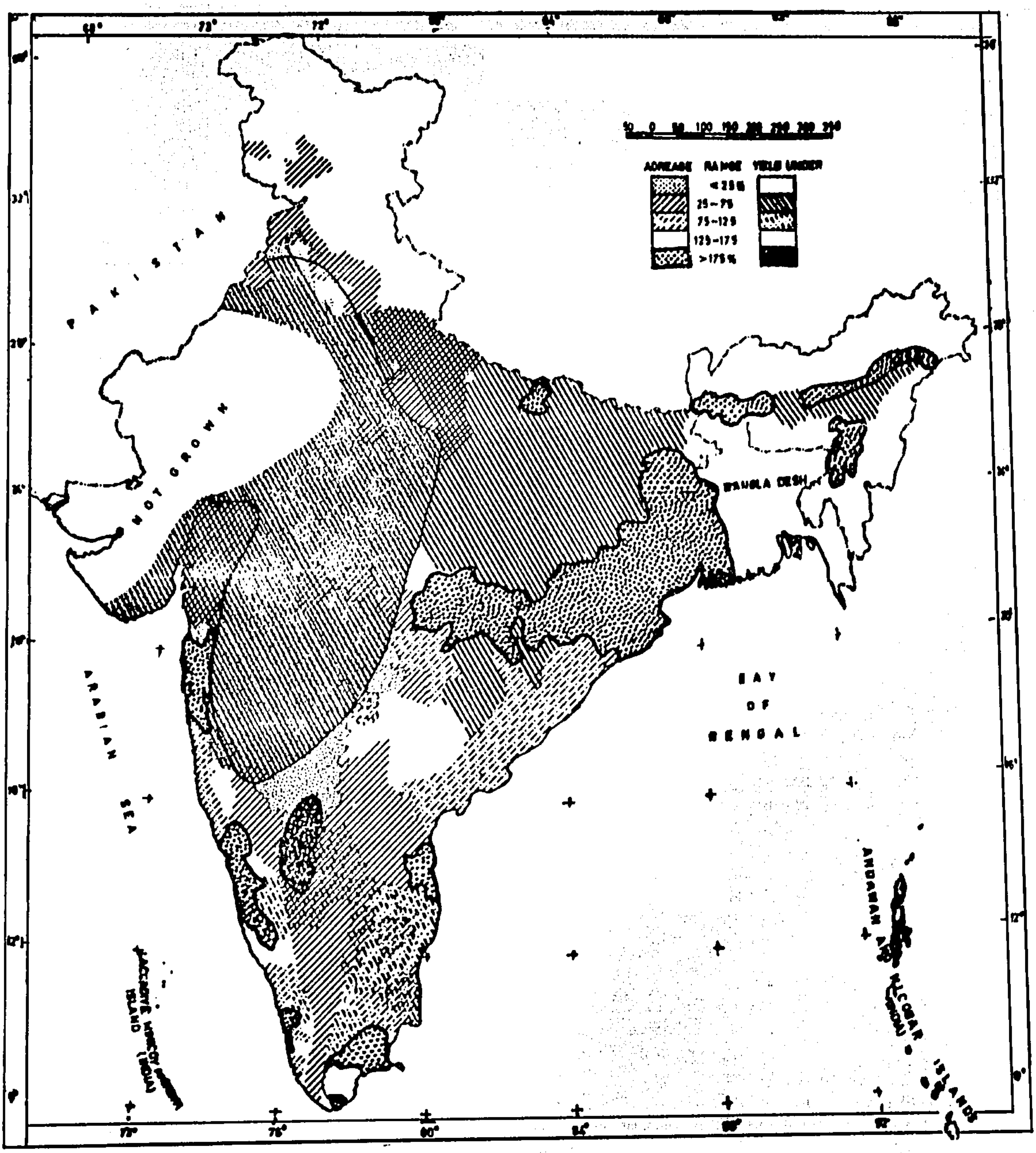
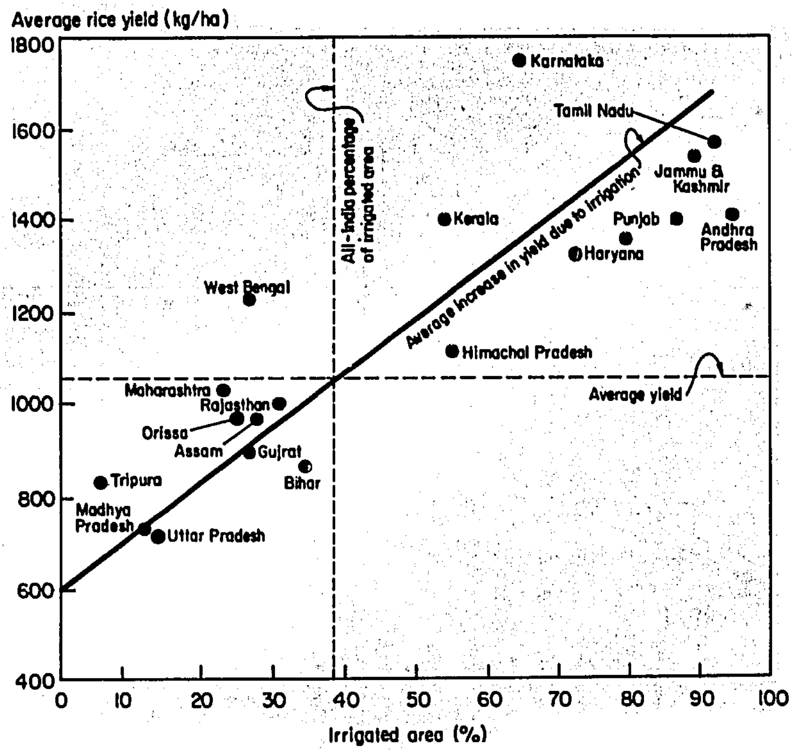


1. Rice map of India.

maintain the same ratio in each state, and that the standard agronomic practices are the same, the yield can be plotted against the percentage of irrigated area (Fig. 2). With the present irrigation system, the average yield increase is threefold for India as a whole. Regions receiving high rainfall show better potential for irrigation, and interior Karnataka, receiving much less rainfall, has given phenomenal yield.



2. State command areas and yields.

RAINFALL PATTERN AND RICE-GROWING SEASONS

Most of the rainfall occurs during the monsoon months June to mid-September in areas receiving southwest monsoon, and mid-September to the end of November in areas influenced by the northeast monsoon. Figure 3 shows the normal dates of the onset and withdrawal of the monsoons (India Meteorological Department 1962).

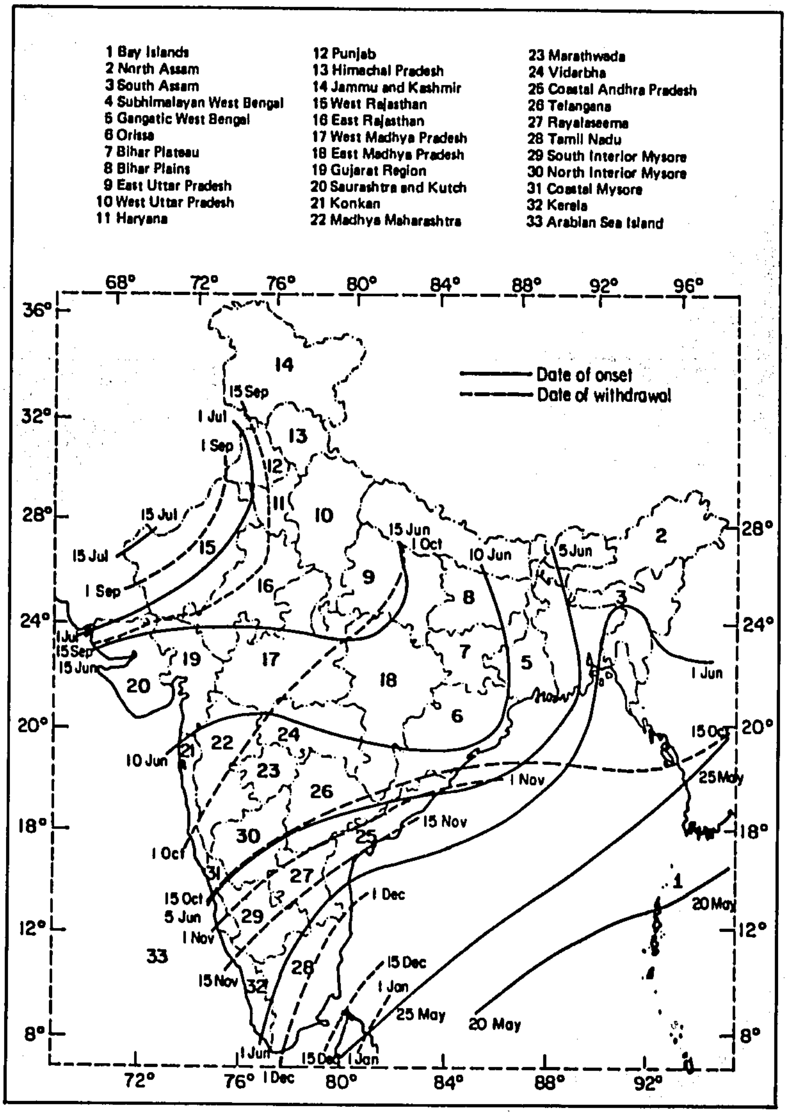
The IMD (1962) codes for monthly rainfall are: A = more than 30 cm; B = 20-30 cm; C = 10-20 cm; D = 5-10 cm; and E = less than 5 cm. Figure 4 shows the coded distribution of rainfall of more than 5 cm/month. The letters within parentheses refer to rainfall for the 4-month period June to September and the number subscripts to the number of consecutive months. The map shows areas where more than one crop of rainfed rice can be grown successfully.

Rice is sown and harvested practically year round in India. Figure 5 shows the sowing and harvesting periods by state (adopted from the Directorate of d Statistics 1972). Eignt states grow rice only in 1 season; 5 cultivate 69% or more in one season. Only 7 and 3% of Karnataka and Uttar Pradesh are planted to summer rice respectively. Kerala has about the same acreage under first and second rice, and 11% under summer rice. Rice is evenly distributed between the first two seasons in Kerala mainly because rainfall is spread over more than 150 days and transplanted rice is used.

In Andhra Pradesh, 96% of the rice area is irrigated and three crops are widely grown. The state accounts for 8.75% of the all-India rice area and 12.0% of India's total rice production (Directorate of Economics and Statistics 1972).

METEOROLOGICAL ASPECTS OF RICE PRODUCTION IN THE METEOROLOGICAL SUBDIVISIONS

Some of the bigger Indian states have more than one pattern of weather conditions. On the basis of rainfall, IMD divided the country into 33 meteorolo-



3. Normal dates of onset and withdrawal of southwest monsoon.

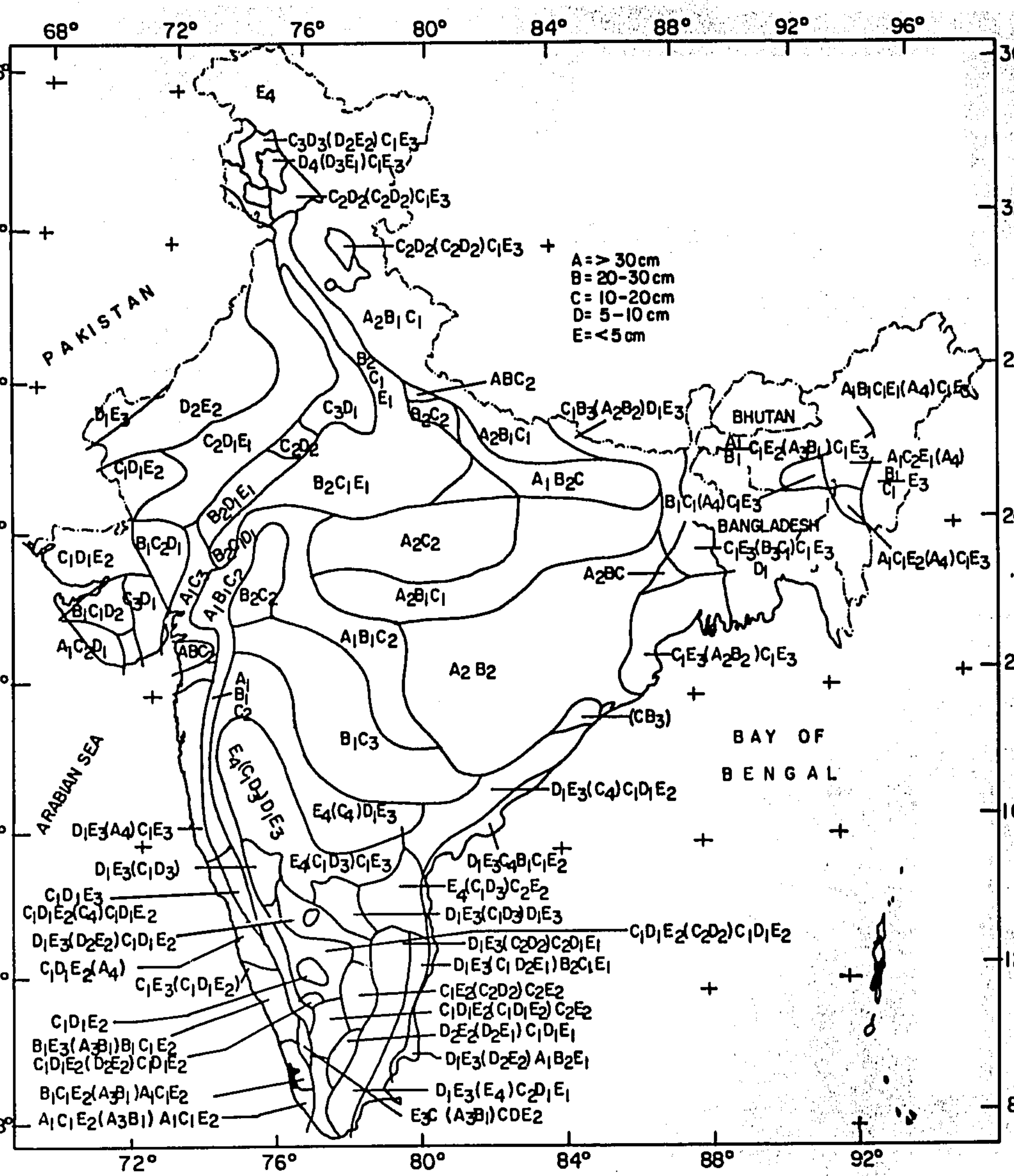
gical subdivisions (Fig. 3) and developed equations to forecast wheat and rice yields on a subdivisional basis. Recently Appa Rao et al (1977) modified the equations developed for the Bihar Plains (Das 1970) and for Kerala (Das and Mehra 1971). The regression equations for the contiguous meteorological subdivisions and their meteorological aspects are given in the Appendix.

Rao and Das (1971) made a comprehensive survey of weather and rice crop yield. Table 1 gives crop statistics for the more important rice growing subdivisions.

West Coast region: Kerala, Coastal Karnataka, and Konkan

The heavy southwest monsoon rains last more than 5 months in Kerala but less than 3 months in Konkan. The regression equations to forecast the yield for Kerala and Konkan are given in the Appendix.

In Kerala, where three crops are raised, the first rice season begins in April. The rainy days in the middle of April lead to better germination and growth in the nursery. In coastal Karnataka with only two crops, the season



4. Monthly rainfall map of India.

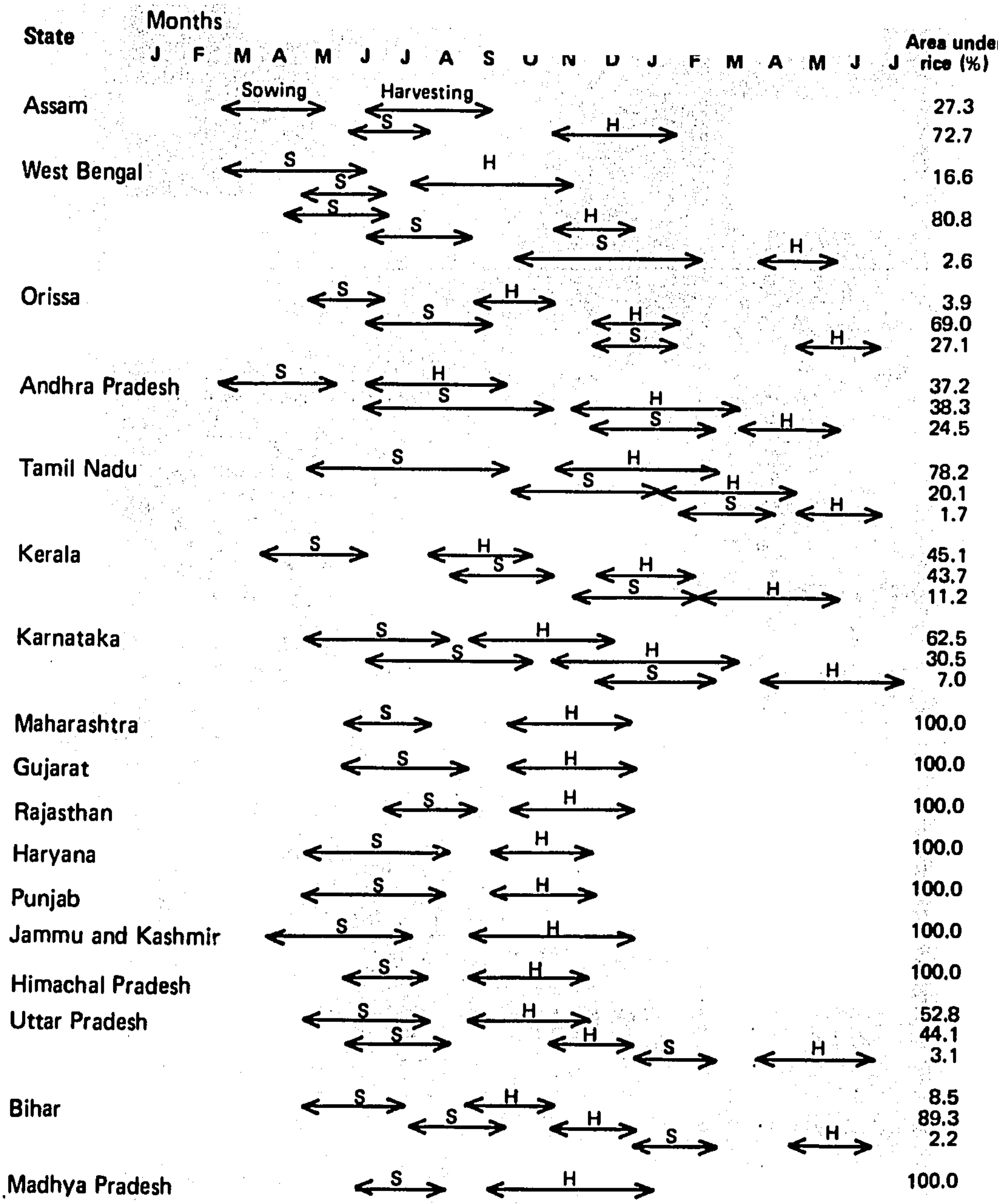
starts in May. The single crop in Konkan is planted in June.

Tamil Nadu

Rice in Tamil Nadu is principally grown as an irrigated crop in all three seasons, and 78% of the rice area is planted to a first crop. Most of the area's monsoon rains are emptied into the Bay of Bengal by rivers like the Cauvery, which arise in the Western ghats and flow eastward This aspect is taken into account in the regression equation on yield in th appendix.

Coastal Andhra Pradesh

The first rice crop in Andhra Pradesh is more important in the northern districts commencing with Guntur. The



5. Periods of sowing (S) and harvest (H) in Indian states.

Table 1. Rice yield and variability in meteorological subdivisions.

Region and meteorological subdivisions	Crop data Period	Years (no.)	Av yield (kg/ha)	Standard deviation	CV	Technological trend present
1. *West Coast Region*						
a. Kerala	1957-72	16	1275	96	7	Yes
b. Coastal Karnataka	1916-64	49	1109	95	9	Yes
c. Konkan	1906-66	57	1205	139	12	Yes
2. Tamil Nadu	1904-65	62	1774	290	16	Yes
3. Coastal Andhra Pradesh	1904-66	63	1748	251	14	Yes
4. *South Central Region*						
a. 1) Interior Karnataka (S)	1941-64	24	1764	372	21	Yes
2) " (N)	1906-64	53	914	202	22	Yes
b. 1) Rayalaseema	1957-73	17	1401	203	14	Yes
2) Telangana	1921-65	41	908	159	18	Yes
c. 1) Madhya Maharashtra	1906-64	56	885	162	18	Nil
2) Marathwada	1955-75	20	532	181	34	Yes
5. *North Central Region*						
a. Vidharbha)						
b. 1) East M.P.)		Not available				
2) West M.P.)						
6. Orissa		Not available				
7. *Eastern Region*						
a. 1) Assam (South)	1946-67	21	933	90	9	Nil
2) Assam (North)	1946-67	21	991	87	9	Yes
b. 1) Sub-Himalayan WB	1947-66	20	989	91	9	Yes
2) Gangetic W. Bengal	1937-66	30	923	141	15	Yes
8. *Gangetic Plain and Bihar Plateau*						
a. 1) Bihar Plateau	1930-64	35	839	132	16	Yes
2) Bihar Plain	1950-72	22	748	179	24	Yes
b. 1) Uttar Pradesh (E)	1921-65	45	632	100	16	Yes
2) Uttar Pradesh (W)	1921-65	45	700	119	17	Yes
9. *Northern Region*						
a. Himachal Pradesh	1951-73	23	888	201	23	Yes
b. Punjab	1921-65	45	1474	223	15	Yes
c. Haryana	1940-65	26	1209	464	38	
10. *Western Region* Gujarat region	1952-74	22	780	198	25	Yes

regression equation in the appendix shows that weather does not influence rice yield much in this subdivision.

South Central Region: South and North (interior) Karnataka, Rayalaseema and Telangana of Andhra Pradesh, and Madhya Maharashtra and Marathwada of Maharashtra

The regression equations in the appendix show that rainfall in North and South (interior) Karnataka is an important meteorological factor in rice production. The maximum temperature in the north Karnataka subdivision and the mean daily minimum temperatures during the harvest in Rayalaseema are also significant meteorological factors. In Madhya Maharashtra, the number of rainy days in July and the mean daily relative humidity at pollination and fertilization are the most important weather factors determining yield.

Eastern Region: Assam (North and South), Sub-Himalayan West Bengal, and Gangetic West Bengal

Rainfall in Assam is an important factor in rice production. High maximum temperatures during grain formation (6-12 Oct.) have a deleterious effect on rice in South Assam, but the high mean range of temperatures are highly beneficial to rice in North Assam.

Rainfall is the dominant weather factor determining yield in West Bengal. Lack of rain in the plateaus or high mean maximum temperatures from 23 to 29 August in the plains that coincide with early flowering depress rice yield in Bihar.

The most important weather aspect in Uttar Pradesh is drought from August to mid-September. The greater mean range of temperatures during flowering depresses yield.

Northern Region: Himachal Pradesh Punjab and Haryana

Punjab and Haryana have similar weather factors; rainfall alone plays a part in determining rice yield. Occasional drought from 1 August to mid-September is important. Himachal Pradesh has a totally different set of meteorological factors, except perhaps presowing rainfall.

Gujarat Region

Gujarat region is in the northwest of the Konkan coast. Cloudiness during flowering is the most important factor. Cloudy weather favors pollination and fertilization.

GENERAL REMARKS

Rainfall plays the most important role in rice production in India. Even in Andhra Pradesh where practically the entire area under rice has irrigation facilities, rainfall determines area and production. A systematic study of rainfall and its influence on rice production will pay rich dividends.

The study by IMD is a statistical approach that should be tempered with information about crop physiology (Sreenivasan 1965).

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APPENDIX

West Coast Region

Kerala: 16 years data with R = 0.98

$$Y = 1410\ x + 11.89\ x_1 - 8.5\ x_2 + 34.32\ x_3 - 49.79\ x_4 + 17.54\ x_T$$

(1.83) (3.06) (2.43) (2.51) (9.88)

Karnataka (Coast): 49 years data with R = 0.895

$$Y = \text{Minus } 32296 - 1.46\ x_1 + 6.01\ x_2 - 32.69\ x_3 + 2336.2\ x_4 - 41.16\ x_5 + 0.67\ x_T$$

(3.16) (3.40) (4.14) (2.06) (2.06) (4.49)

Konkan: 57 years data with R = 0.87

$$Y = \text{Minus } 101154 + 3.86.27\ x_1 + 87.89\ x_2 - 17.76\ x_3 + 7.536.4\ x_4 - 140.53\ x_5$$

(3.20) (5.09) (2.75) (2.78) (2.80)

Where, *R* stands for Multiple Correlation Coefficient and the independent variables with their suffixes are:

Suffix of x	Kerala	Karnataka (Coast)	Konkan
1	Rainy days during 13/4 to 19/4	Rainfall in June	Log of rainfall in June to August
2	Rainy days during 8/7 to 3/8	Restricted rainy* days during 1/7 to 15/9	Mean monthly cloudiness in July to September at 0830 h IST
3	Mean temperature during 13/6 to 21/6	Floods** and droughts in Aug. and Sept.	Floods*** and droughts in July to Sept.
4	Minimum temperature during 15/7 to 27/7	Mean maximum temperature in July-August	Mean temperature of July to August
5	-	Square of x_4	Square of x_4
T	Technological trend in the series.		Nil

*Rainfall of 5 cm or more in 24 h followed by any rain the next day is counted as 1.
**Daily average rainfall less than 0.25 cm consecutively for 10-14 days = 1; 15-17 days = 2; 18-21 days = 4; 22-24 days = 6; 25-28 days is given a value of 8 for drought. Floods are defined as a) 5 cm or more of rain for 3 or more consecutive days, b) 15 cm or more of rain for 2 or more consecutive days, and c) 20 cm or more of rain on a single day.
***Flood is defined the same as above. Drought: 8 days or more = 2, 11-14 days = 4, and more than 14 days = 6.

Tamil Nadu: 62 years data with R = 0.882

$$Y = 1335.3 + 26.23\ x_1 + 42.66\ x_2 - 17.23\ x_3 - 0.37\ x_4 + 0.46\ x_5 + 1.33\ x_6$$

(3.33) (3.65) (1.03) (1.07) (5.62) (5.58)

Values in parentheses are *t* values of regression coefficient. The independent variables are: x_1 and x_2 = coded rainfall in the Western ghats for the second half of May and June (code figure 0 for less than 25% of normal; code 1 to 8 for the class interval 25% to 50%, 50% to 70%, 70% to 90%, 90% to 110%, 110% to 130%, 130% to 150%, 150% to 200%, and 200% or more, respectively; x_3 for mean maximum temperature for July and August; x_4 for mean minimum temperature in August and September; x_5 and x_6 technological trend. Temperatures as a factor seem to be of least importance.

Coastal Andhra Pradesh: 63 years data with R = 0.911

$$Y = 1250.9 + 6.54\ x_1 - 27.40\ x_2 + 30.07\ x_3 - 0.81\ x_4 - 13.74\ x_5 + 1.25\ x_6 + 1.44\ x_7$$

(1.15) (1.75) (1.53) (1.10) (1.26) (8.73) (6.77)

Where, x_1 is rainy days in July; x_2 the number of occasions in August and September when dry weather or weekly rainfall not exceeding 0.88 cm persists for 14 days with 0 value in the sliding scale: 15 to 21 days = 1, 22 to 28 days = 3, 29 to 32 days = 4, 33 to 35 days = 6, 36 to 39 days = 8, 40 to 42 days = 10, and >42 days = 12; x_3 for rainy days in October; x_4 the square of rainy days; x_5 the mean temperature for October; x_6 and x_7 for technological trends.

South Central Region:

Karnataka:

(i) *South*: 24 years data with R = 0.967

$$Y = \text{minus } 62154 + \underset{(2.42)}{52.93\, x_1} + \underset{(4.21)}{51.49\, x_2} - \underset{(2.19)}{42.89\, x_3} + \underset{(1.75)}{45599.7\, x_4} - \underset{(1.76)}{83.57\, x_5} + \underset{(9.51)}{0.76\, x_t} \text{ and}$$

(ii) *North*: 53 years data with R = 0.924

$$Y = \text{minus } 69537 + \underset{(3.56)}{25.47\, x_1} - \underset{(2.16)}{0.40\, x_2} - \underset{(9.32)}{64.26\, x_3} + \underset{(3.75)}{4704.2\, x_4} - \underset{(3.74)}{78.31\, x_5} + \underset{(8.20)}{0.81\, x_t}$$

Where the independent variables with their suffixes are:

Suffix of x	South Karnataka	North Karnataka
1	June Rf in inches	July Rf in inches
2	September Rf	Square of June to August Rf in inches
3	Occasion of drought in July-August	Occasion of drought in August-September
4	Mean maximum temperature in °C in July-August	Mean maximum temperature in °C in July-September
5	Square of x_4	Square of x_4
t	Technological trend in the series	

The occasions of drought are defined as periods with daily rain less than 0.25 cm and coded as follows:

	South		*North*	
a)	10 - 14 days	1	8 - 10 days	1
b)	15 - 17 days	2	11 - 14 days	2
c)	18 - 21 days	4	15 - 17 days	4
d)	22 - 24 days	6	18 - 21 days	6
e)	25 - 28 days	8	22 - 24 days	8
f)	More than 28 days	10	25 - 28 days	11
g)	-		More than 28 days	14

(iii) *Rayalaseema*: 17 years data - R = 0.94
Mean yield 1400.7 kg/ha (Y)

$$Y = 2479.65 + \underset{(3.72)^{**}}{31.61\, x_1} + \underset{(2.32)^{*}}{15.99\, x_2} - \underset{(3.17)^{**}}{74.93\, x_3} + \underset{(3.49)^{**}}{18.38\, x_t}$$

Where, x_1 = total number of rainy days during 1-27 June
x_2 = total number of rainy days during 27/9 to 25/10
x_3 = mean daily minimum temperature (°C) from 3/11 to 9/11
x_4 = technological trend.

*Significant at 5% level; **Significant at 1% level.

(iv) *Telangana*: Rice in this subdivision was the earliest studied with 41 years data (1921 to 1965). The average yield is 810 lb/acre (908 kg/ha). The regression equation on yield Y in lb/acre is

$$Y = 628.7 + \underset{(2.08)^{*}}{32.48\, x_1} - \underset{(2.05)}{2.161\, x_2} - \underset{(3.82)}{31.862\, x_3} + \underset{(3.02)}{18.673\, x_4} - \underset{(2.83)}{6.906\, x_6} + \underset{(3.22)}{28.201\, x_7} + \underset{(5.24)}{42.956\, x_t}$$

Where, x_1 is rf during the period 1 to 21 July; x_2 square of x_1; x_3 is rf during 30 July to 9 August; x_4 rf in 11 to 26 August; x_5 rf in 3 to 14 Sept.; x_6 rf in 6 to 15 Oct.; and x_t technological trend. *t value for the partial regression coefficient. MCC is 0.854.

(v) *Madhya Maharashtra*: The regression formula for yield Y in lb/acre obtained from 56 years data is:

$$Y = 429.54 + \underset{(9.11)}{33.755\, x_1} - \underset{(4.47)}{49.731\, x_2} + \underset{(2.24)}{9.646\, x_3}$$

Where, x_1 is rainy days in July; x_2 = Occasion of drought during August; and x_3 = rainy days during 16 to 30 September.

Drought is defined as: daily rainfall less than 0.25 cm consecutively for a) 8-10 days = 2; b) 11-14 days = 4; and c) more than 14 days = 6.

R = 0.901 accounting for 81% of total variability. Values in parentheses are *T* values of regression coefficients.

(vi) *Marathwada*: With 20 years data yield

$$Y \text{ in kg/ha} = 1528.4 + 33.24\,x_1 - 129.28\,x_2 + 10.45\,x_3 + 21.04\,x_4 + 30.40\,x_t$$
$$(2.94)^{**} \quad (2.65)^{*} \quad (4.99)^{**} \quad (4.99)^{**} \quad (9.27)$$

Where, x_1 = Mean daily maximum temperature (°C) during 14 to 20 July (elongation stage)
x_2 = Mean daily minimum temperature (°C) during 10 to 18 August (end of elongation)
x_3 = Mean daily relative humidity during 10 to 22 September (flowering phase)
x_4 = Total number of restricted rainy days during 5 to 13 October (grain formation) and x_t = technological trend.

*Significant at 5% level; **Significant at 1% level; MCC is 0.96 accounting for 92% of total variation in yield.

Assam: With R = 0.93 yield in kg/ha.

$$Y = 2501.8 + 7.49\,x_1 + 9.26\,x_2 + 14.06\,x_3 + 39.14\,x_4 - 12.89\,x_5 - 9.491\,x_6 \text{ for South}$$
$$(2.85) \quad (2.35) \quad (1.88) \quad (2.85) \quad (2.40) \quad (3.18)$$

Assam with R = 0.94 and

$$Y = 1390.4 + 20.04\,x_1 + 18.35\,x_2 - 16.50\,x_3 - 24.02\,x_4 - 15.66\,x_5 + 33.93\,x_t$$
$$(3.27) \quad (3.11) \quad (1.72) \quad (2.73) \quad (2.69) \quad (5.12)$$

Where:

	South Assam	North Assam
x_1 =	Rainfall 1 to 7 May	Restricted rainy days during 11-17 May
x_2 =	Rf 23 to 30 July	Rf 21-27 July
x_3 =	Rd 2 to 8 Oct.	Rd 3-9 August
x_4 =	Mean Cl amount 17-25 July	Mean range of T 8-23 Sept.
x_5 =	Mean T_x: 11-31 July	Mean range of T 5-11 Oct.
x_6 =	Mean T_x: 6-12 Oct.	--
x_t =	Nil	Technological trend

West Bengal: Sub-Himalayan West Bengal with R = 0.827 yield in lb/acre.

$$Y = 3945.3 - 148.9\,x_1 + 4.32\,x_2 - 11.88\,x_3 + 11.64\,x_4 - 62.33\,x_5 + 0.75\,x_t$$
$$(1.10) \quad (1.17) \quad (1.34) \quad (2.27) \quad (1.59) \quad (2.08)$$

Gangetic West Bengal with R = 0.818 on yield in kg/ha of

$$Y = 668.8 + 17.61\,x_1 - 134.41\,x_2 + 11.33\,x_3 + 15.24\,x_t$$
$$(2.98) \quad (3.77) \quad (2.35) \quad (2.98)$$

Where:

	Sub-Himalayan	Gangetic West Bengal
x_1	Restricted Rf of 5 cm or more followed by any rain next day	Rf in June (In)
x_2	Square of x_1	Occasions of drought*
x_3	Occasions of drought**	Rd in 16/9 to 15/10
x_4	Rd in 16/9 to 15/10	--
x_5	Mean T_x in 16/8 to 15/9	--
x_t	Technological trend in the series.	

*When there is not a single day of Rf more than 0.25 cm within a continuous period of 8-14 days, it is taken as an occasion of drought marked by dummy figure 1. Similarly 15-21 days gets dummy figure 3, and more than 21 days is dummy figure 6.
**The number of occasions when dry weather or Rf of weekly Rf total not exceeding 0.44 cm persisted for 7 days = 0, 8-11 days = 1, 12-14 days = 3, 15-18 days = 6, and 19-21 days = 10 dummy figures are allotted.

Bihar Plateau and Gangetic Plains

Bihar Plateau lying adjacent to Gangetic West Bengal has regression on yield Y lb/acre as

$$Y = 697.7 - 43.87\,x_1 + 3.01\,x_2 + 28.36\,x_3 - 62.34\,x_4 + 10.33\,x_t$$
$$(2.07) \quad (2.00) \quad (4.00) \quad (3.95) \quad (3.19)$$

with R = 0.82 while in Bihar plains the regression on yield Y kg/ha as revised is:

$$Y = 2182.8 - 18.23\,x_1 - 51.56\,x_2 + 14.98\,x_3 - 4.59\,x_4 + 27.47\,x_t$$
$$(2.42) \quad (3.02) \quad (2.43) \quad (3.25) \quad (10.09)$$

with R = 0.96

The values in parentheses are as visual, the t-test values for the parameters and the x's are:

	Bihar Plateau	Bihar Plains
x_1	Rf in June in inches	Rd during 29/6 to 5/7
x_2	$(x_1)^2$	Mean T_x (°C) during 23/8 to 29/8
x_3	Rd during 16/9 to 15/10	Rd during 29/9 to 12/10
x_4	Occasions of drought* in July-August	Rf in mm during 3 to 11 Nov.
x_t	Technological trend in the series	

*When there is no day of rainfall more than 0.13 cm within a continuous period of 7-10 days it has been taken as an occasion of drought marked by dummy figure 1. Similarly if this period is 11-14 days = 3, 15-21 days = 5, and more than 21 days = 8.

Uttar Pradesh (U.P.) - The two regression formulas on yield 'Y' in pounds per acre for the East and West U.P. are:

$$Y = 473.5 + \underset{(3.56)}{28.48\, x_1} - \underset{(3.38)}{1.199\, x_2} + \underset{(2.22)}{16.29\, x_3} - \underset{(2.34)}{0.197\, x_4} + \underset{(4.60)}{8.45\, x_5} + \underset{(2.02)}{12.12\, x_6} - \underset{(6.98)}{45.16\, x_7} + \underset{(2.15)}{14.12\, x_8} + \underset{(2.37)}{8.30\, x_t}$$

U.P. with R = 0.924 and

$$Y = 463.1 + \underset{(3.48)}{6.49\, x_1} + \underset{(4.06)}{29.05\, x_2} - \underset{(4.69)}{24.24\, x_3} - \underset{(2.80)}{6.19\, x_4} + \underset{(4.16)}{14.09\, x_5}$$ for West U.P. with R = 0.893

The values in parentheses are t-values, and the independent variables are:

	East U.P.	West U.P.
x_1 :	Rf during 18/7 to 10/8	Rf during 26/7 to 24/9
x_2 :	Square of x_1	Mean Cl amount during 27/7 to 1/8
x_3 :	Rd in 2/7 to 31/8	Occasions of drought* during 1/8 to 15/9
x_4 :	Square of x_3	Mean range of T for the period 22/9 to 29/9
x_5 :	Rf 24/8 to 30/9	
x_6 :	Mean Cl amount for the period 1/8 to 15/9	
x_7 :	Occasions of drought* during 1/8 to 15/9	
x_8 :	Mean range of T in Sept.	
x_t :	Technological trend in the series	

* When there is no day of rainfall more than 0.25 cm in a continuous period of 8-10 days, it has been taken as an occasion of drought marked by dummy figure 1. Similarly 11-14 days = 2, 14-18 days = 4, 19-21 days = 7, and more than 21 days = 10.

Northern Region

(i) For H.P., yield 'Y' in kg/ha

$$Y = 982.6 + \underset{(2.96)}{55.6\, x_1} - \underset{(3.09)}{75.6\, x_2} + \underset{(2.07)}{0.63\, x_3} + \underset{(2.44)}{21.68\, x_t}$$

with R = 0.91

Where, x_1 = Mean cloud amount during 3-11 Sep.
x_2 = Total number of rainy days during 27/7 to 4/8
x_3 = Total rainfall in 12/5 to 17/6 and
x_t = Technological trend.

For Punjab with yield 'Y' in Rs/acre

$$Y = 1272.3 + \underset{(2.16)}{29.29\, x_1} + \underset{(2.48)}{7.64\, x_2} - \underset{(4.39)}{19.7\, x_3} - \underset{(5.09)}{20.60\, x_4} + \underset{(2.02)}{23.07\, x_5} + \underset{(15.29)}{10.21\, x_t}$$

with R = 0.938 and

For Haryana with yield 'Y' in lbs/acre

$$Y = 461.9 + \underset{(2.32)}{75.21\, x_1} + \underset{(2.63)}{3.67\, x_2} - \underset{(2.13)}{7.67\, x_3} + \underset{(5.70)}{37.74\, x_4} + \underset{(14.10)}{39.83\, x_t}$$

with R = 0.981

		Punjab	*Haryana*
x_1	:	Rf in 21 to 27 June	Rf in 19 to 25 June
x_2	:	Rf in 4 to 31 July	Rf in 10 to 23 July
x_3	:	Drought during* 1/8 to 15/9	Drought during* 1/8 to 15/9
x_4	:	Rf during 25/9 to 9/10	Rd during 3/8 to 13/8
x_5	:	Rf during 1-7 June	
x_t	:	Technological trend in the series.	

The figures in parentheses are t-test values.
*With no day of rainfall of more than 0.25 cm for 8-10 days, the drought is marked with a dummy figure 1. Similarly for 11-14 days = 2, 15-18 days = 4, 19-21 days = 7, and more than 21 days = 10.

Gujarat

$$Y = \text{minus } 212.9 + \underset{(3.09)^{**}}{0.89\, x_1} + \underset{(4.01)^{**}}{84.81\, x_2} + \underset{(2.41)^{*}}{39.76\, x_3} + \underset{(1.55)}{0.60\, x_4} + \underset{(4.46)^{**}}{7.54\, x_t}$$

with R = 0.87

Where, Y = Yield (kg/ha)
x_1 = Total Rf (mm) during 1-10 July
x_2 = Mean cloud amount during 8-18 Sep.
x_3 = Mean temperature range (°C) during 12-18 August
x_4 = Total Rf (mm) during 15-27 July
x_t = Technological trend

*Significant at 5% level; **Significant at 1% level.

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Agrometeorology of three rice regions of the Indus Plain

Mohammad Rafiq

Northeastern Punjab, Northern Sind, and the Indus Delta are the main rice regions on the Indus Plain. The rice growing season in Northeastern Punjab is characterized by mildly hot days, high humidity, partly cloudy weather, and rain. Northern Sind is very hot and cloudless, and humidity is low. The Indus Delta has hot days, sea breezes, high humidity, and some cloudiness. Northeastern Punjab grows high quality, fine-grained, and aromatic rice, whereas the two other regions produce coarse rice. The yield potential of Northern Sind and the Indus Delta is very high; that of Northeastern Punjab is moderate to high.

Northeastern Punjab, Northern Sind, and the Indus Delta are the main rice regions on the Indus Plain (Fig.1). Each region's agrometeorological characteristics are described briefly by Rafiq (1971, 1976). This paper describes the characteristics in greater detail. However, not all relevant data are available.

Northeastern Punjab (region 1)

Region 1, comprising the northeastern part of the Indus Plain, is nearly level with a very gentle slope from northeast to southwest. The climate is continental subhumid subtropical. The climatic data for Lahore, a representative station, are given in Table 1. The monthly mean maximum temperature for the rice season (June to mid-November) ranges between 28.3°C and 41°C. The monthly mean minimum temperature ranges between 8.5°C and 26.1°C. The mean total rainfall during this period is about 370 mm, while evaporation from free water surface is about 700 mm. The rainfall occurs as high intensity showers (up to 200 mm in 24 hours) separated by dry spells. Although rains provide a high proportion of the total water required, irrigation is necessary for growing rice. The mean monthly sunshine hours during the rice season ranges between 264 and 290, showing that the weather remains partly cloudy. The relative humidity is high, 70 to 90% in the morning and 50 to 70% in the afternoon.

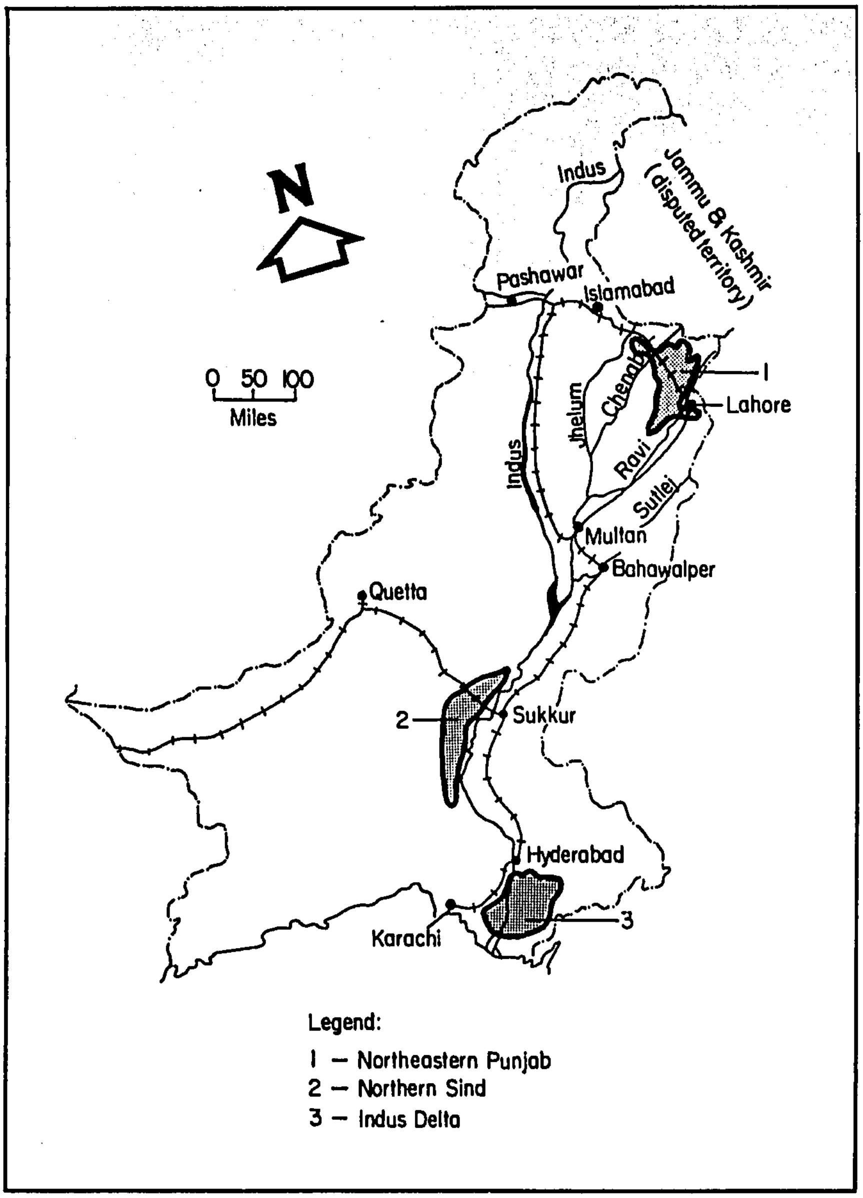
This region is famous for the high-quality, fine-grain, aromatic rice, locally known as *basmati*, which grows on a very high proportion of rice land. Some IRRI varieties and local coarse rice varieties are also grown. The highest yield of an IRRI variety (IR6) is about 6.5 t/ha, while that of *basmati* is about 3.8 t/ha. Although cloudiness may inhibit yield, it possibly favors the fine-grain, aromatic variety which is limited to this region. Low temperatures during crop maturity may also favor high quality rice.

Northern Sind (region 2)

Part of the central Indus Plain, Northern Sind is an overlapping of the backswamp of the Indus river and a series of basins of a piedmont plain. The land has very little north to south slope and drainage is poor.

The climate is continental arid, hot subtropical. The climatic data for Khairpur, a representative station, are given in Table 2. The mean monthly maximum temperature during the rice season (June-October) ranges between 36.5°C and 45.2°C, and the mean minimum temperature ranges mostly between 18°C and 27.5°C. The mean total rainfall during this period is 76 mm, whereas

Basic Soil Investigations, Soil Survey of Pakistan, P.O. Shahnoor, Multan Road, Lahore, Pakistan.



1. Rice regions of the Indus Plain, Pakistan.

evaporation is about 970 mm. The mean relative humidity ranges between 65 and 77%. The monthly mean sunshine (285-325 hours) shows almost complete absence of cloudiness. IRRI and local coarse rice varieties are grown in this region. High temperature and continuous sunshine are conducive to very high yields of coarse varieties but unfavorable for fine-grain varieties. The high sunshine hours favor a high rate of photosynthesis, which is probably responsible for the world's highest yield of IRRI rice (about 14 t/ha) recorded in this area. The total water required for rice in this region is much higher than in Northeastern Punjab, but about equal to that in the Indus Delta.

Indus Delta (region 3)

Region 3 includes the entire Indus Delta. Imperfect to poor drainage due to very little general slope, a series of basins, very slow soil permeability,

Table 1. Climatic data for Lahore, Pakistan.[a]

Month	Mean daily temperature (°C) Max	Min	Mean monthly rainfall (mm)	Mean monthly evaporation (mm)	Relative humidity (%) 8 A.M.	5 P.M.	Mean	Mean monthly sunshine (h)
Jan	20.0	4.4	35	39	65	41	53	215.7
Feb	22.7	6.9	25	49	63	44	54	221.4
Mar	28.1	11.7	20	85	70	46	58	246.6
Apr	34.7	17.3	14	122	80	48	64	278.6
May	39.8	23.3	15	150	85	61	63	310.8
Jun	41.0	26.1	40	163	86	69	78	273.4
Jul	37.5	26.7	138	150	88	70	79	237.1
Aug	36.1	25.9	130	130	89	71	80	240.8
Sep	36.3	22.8	56	114	87	72	80	264.3
Oct	34.4	15.4	5	86	76	55	66	289.9
Nov	28.3	8.5	2	54	67	45	56	263.3
Dec	22.4	10.3	11	40	71	51	61	228.1

[a]Source: Meteorological Department, Regional Office, Lahore.

Table 2. Climatic data for Khairpur, Pakistan.[a]

Month	Mean daily temperature (°C) Max	Min	Mean monthly rainfall (mm)	Mean monthly evaporation (mm)	Mean relative humidity (%)[b]	Mean daily sunshine[b] (h)
Jan	23.6	4.8	5	94	62	282.1
Feb	27.9	10.0	8	114	61	240.8
Mar	32.7	14.0	3	147	57	285.2
Apr	38.5	19.4	2	186	54	288.0
May	42.9	24.6	0	226	56	325.5
Jun	43.6	26.9	2	236	69	312.0
Jul	45.2	27.5	46	216	77	285.2
Aug	40.5	26.3	28	198	77	291.4
Sep	38.3	24.1	0	181	77	285.0
Oct	36.5	18.0	0	142	65	306.9
Nov	29.6	11.1	0	102	63	270.0
Dec	23.5	6.1	2	76	67	266.6

[a]Source: Lower Indus Project Report Vol. I. Climate, 1965. Hunting Technical Services. Water and Power Development Authority, Lahore, Pakistan. [b]Data for Sukkur, about 15 km north of Khairpur.

and the availability of river water for irrigation have made rice the main crop.

The climate of the region is marine arid subtropical. The climatic data for Karachi and Hyderabad are given in Tables 3 and 4. The climatic conditions change with distance from the sea: Karachi represents areas near the sea and Hyderabad, the northern part of the region.

The mean maximum temperature at Karachi during the rice season (June-October) ranges mostly between 31.4°C and 35°C. In Hyderabad June is slightly hotter, with 40.5°C. The monthly mean minimum temperatures are nearly the same (21°C to 28°C) at the 2 stations. The mean total rainfall during the rice season at the two sites ranges from 150 to 210 mm, whereas total evaporation is

Table 3. Climatic data for Karachi, Pakistan.[a]

Month	Mean daily temperature (°C)		Mean monthly rainfall	Mean monthly evaporation	Relative humidity (%)			Mean monthly sunshine
	Max	Min	(mm)	(mm)	8 A.M.	5 P.M.	Mean	(h)
Jan	35.1	10.4	8	94	59	35	47	275.8
Feb	27.4	12.9	13	102	65	42	54	252.0
Mar	31.4	17.6	5	155	68	45	57	279.0
Apr	34.7	21.7	2	193	72	47	60	280.0
May	35.8	25.7	2	208	74	61	68	309.2
Jun	34.8	28.0	9	178	76	68	72	240.8
Jul	32.9	27.2	100	127	81	72	77	179.5
Aug	31.4	26.2	47	127	82	72	82	151.8
Sept	32.1	25.1	23	142	81	69	75	226.8
Oct	34.4	20.9	33	152	71	49	60	289.1
Nov	32.1	15.7	3	119	59	40	50	278.8
Dec	27.3	11.8	6	94	62	41	52	270.4

[a]Source: Meteorological Department, Regional Office, Karachi.

Table 4. Climatic data for Hyderabad, Pakistan.[a]

Month	Mean daily temperature (°C)		Mean monthly rainfall	Mean monthly evaporation	Mean relative humidity (%)	Mean monthly sunshine
	Max	Min	(mm)	(mm)		(h)
Jan	24.4	10.0	5	95	42	263.0
Feb	27.8	11.6	5	103	44	251.4
Mar	33.3	17.2	5	180	38	295.6
Apr	39.4	22.2	2	212	36	295.9
May	42.2	25.5	5	240	44	315.0
Jun	40.5	27.8	10	225	54	267.9
Jul	36.7	15.5	75	195	51	247.3
Aug	35.5	26.1	50	185	62	247.8
Sep	36.1	25.0	15	173	57	277.4
Oct	36.7	21.1	0	170	44	303.6
Nov	31.1	15.5	2	118	40	280.0
Dec	25.5	11.1	2	95	44	268.6

[a]Source: Lower Indus Report Vol. I. Climate, 1965. Hunting Technical Services. Water and Power Development Authority, Lahore, Pakistan.

720 to 950 mm. The total sunshine hours during the rice season is 1088 at Karachi and 1344 at Hyderabad. Near the coast, the mean relative humidity ranges between 71 and 82% in the morning and between 49 and 72% in the afternoon. The mean relative humidity in the north ranges between 51 and 62%.

The main agroclimatic features of this region -- high humidity, high temperature with small diurnal variation, and high sunshine hours -- make it suitable for coarse rice varieties. The highest yields obtained are 8.5 t/ha which are higher than those of Northeastern Punjab but lower than those of Northern Sind. High temperatures in October are possibly unfavorable for *basmati*.

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Agroclimatic constraints to dryland rice production in West Africa

T. L. Lawson

More land is being brought under dryland rice production in West Africa to meet an increasing grain demand. However, yields have actually been declining, probably because of the failure to judiciously select production areas by matching environmental attributes with crop requirements.

An assessment of the aerial and edaphic environments indicates that rainfall variability, moderate to high evaporation, and the low moisture-holding capacity of most of the soils interact to cause occasional moisture stress during the rice cropping season. Low solar radiation levels coupled with high air and soil temperatures reduce photosynthesis and dry matter production. Winds conducive to photosynthesis are reduced in the canopy during periods of calm, while strong gusts during thunderstorms damage rice crops through lodging.

These factors constitute yield constraints and their indirect effects may enhance their impact. Careful site selection and the use of improved varieties and cultural practices still offer a viable approach to yield improvement.

Rice is not really a staple food in West Africa except in specific areas like Liberia, Sierra Leone, Gambia, and parts of Senegal and Ivory Coast (USDA/AID 1968, Aw 1978). However, demand for the cereal is increasing in the region because of reportedly the population's increasing food demands and a detectable change in diet arising from socioeconomic changes (USDA/AID 1968, Winch and Kivunja 1978). Although the new demand is being met largely by increased importation (Aw 1978), the need to conserve meager foreign exchange has given rise to serious efforts to increase local production.

Very modest gains have been made by increasing the total land area devoted to rice (Chandler, Jr. 1979). But in spite of the increased availability of materials with better genetic potential (IRRI 1975, Chabrolin 1974, Abifarin et al 1972), yields have been declining because of a failure to come to terms with environmental constraints. The aerial and edaphic environments play a major role in determining yield because they strongly influence the physiological expression of whatever genetic potential the crop may have (Landsberg 1972, Hogg 1971).

This paper will examine the physical attributes of the West African environment that constitute actual or potential constraints to rice production. Focus is on dryland rice, which accounts for 75% of the total rice area (Abifarin et al 1972). The term dryland rice, in this context, describes rice grown on well-drained soil where the groundwater throughout the year lies well below the soil layers exploited by the crop roots. The crop water requirements are thus satisfied solely by natural rainfall (Jacquot 1972). The term is synonymous with *pluvial* rice used by Moormann and van Breemen (1978), but excludes *phreatic* rice (Buddenhagen 1978, WARDA 1975).

THE WEST AFRICAN ENVIRONMENT AND DRYLAND RICE PRODUCTION

Moisture conditions

Rice requires ample and regular moisture because of its semiaquatic nature (Moormann and van Breemen 1978) and also because of the relative shallowness of its root system (Le Buanec 1975). The peculiar characteristics of rainfall, the prevailing high evaporative demand, and the relatively poor physical characteristics of the soils in the West African environ-

International Institute of Tropical Agriculture, Ibadan, Nigeria.

ment interact to cause occasional moisture stress during the dryland rice cropping season.

Rainfall. Rainfall within the region is closely associated with the movement of a pseudofrontal zone, the intertropical convergence zone (Harrison Church 1957, Flohn 1960b). Moisture conditions conducive to the development of rain-sustaining clouds trail the *front* for about 400-500 km, and extend a comparable distance south of it (Flohn 1960, Lawson 1969). The zone of maximum precipitation correspondingly moves north and south across the region with the displacement of the convergence zone; it also undergoes shorter term fluctuations in association with the dynamic changes in the system.

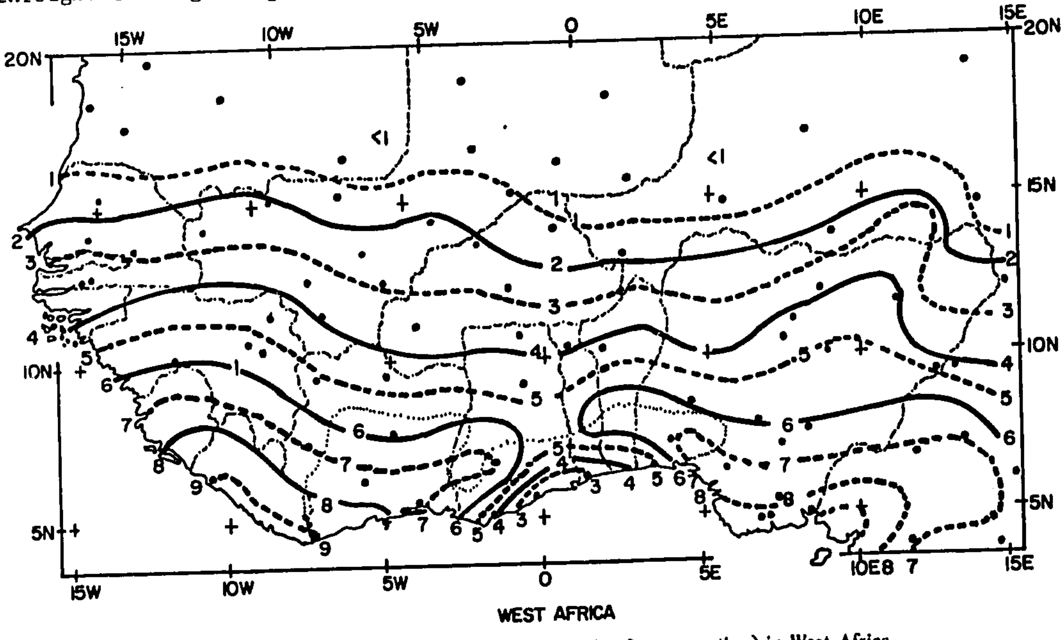
Temporal and spatial variabilities in precipitation are well marked. In the northern part of the region with a monomodal rainfall, both the onset and cessation of the rains are irregular.

South of this zone and roughly between latitude 8°N and the coast and longitudes 7 1/2°W and 5°E, a pronounced drop in rainfall in July or August breaks the period March or April-October into two distinct cropping seasons and creates a bimodal rainfall zone (delineated by small dots in Fig.1). Neither season is strictly suitable for dryland rice, even based on a minimum crop requirement of 200 mm rainfall/month throughout the growing season (Brown 1969). Furthermore, much of the zone is prone to drought spells within the cropping season. The probability of such spells appears high in May (Fig.2; Hedley and Udoka, unpublished). Similar occurrences at Bouake, Ivory Coast, farther to the west are locally referred to as *le trou de Mai* (literally the "hole of May" Gigou 1973).

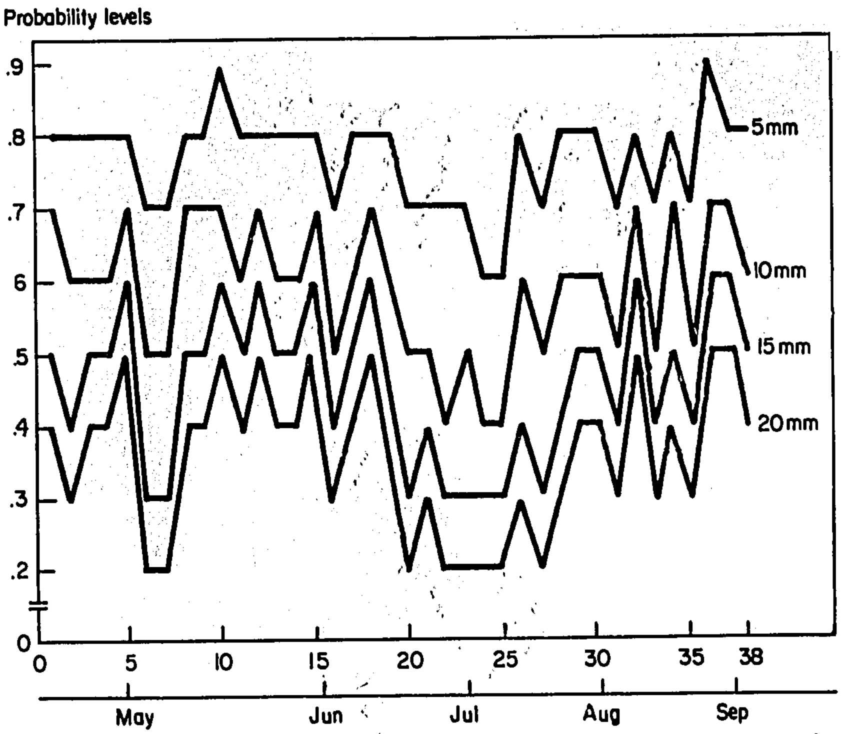
A third rainfall zone, characterized as pseudobimodal, prevails east and west of the preceding zone, more or less forming a continuum with the first. The August decline in precipitation in this zone is not sufficient to constitute a break in the cropping season. The zone therefore enjoys a longer season (March-October or November) with an annual rainfall of ≥ 1,500 mm and more rainy days.

The rains in all three zones are intense. Maximum values exceed 50 mm/hour, with short peak intensities above 100 mm/hour (Charreau and Nicou 1971, Brunet-Moret 1966). At International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria, peak intensities of 75 mm/hour have been exceeded an average of 12 times/year between 1972 and 1977 (Lawson, unpubl.).

Such high rainfall intensities have a predictable effect on the poorly structured soils that are predominant in the region, particularly once surface cover is removed (Kowal and Kassam 1978, Lal 1973). Frequent removal of fine and colloidal materials through excessive



1. Number of months with *positive* water balance (precipitation ≥ evaporation) in West Africa. .... = bimodal rainfall/cropping area.



2. Trend in probabilities of given rainfall amount (after Hedley and Udoka 1972). Time in 4-day periods.

runoff and erosion leaves the coarser fraction in the surface layers. Most of the soils are thus sandy, poorly graded, and low in organic matter; their clay fraction consists mainly of nonswelling kaolinitic clay (Moormann and Veldkamp 1978, Le Buanec 1975). They may be marked by ferrugineous concretions or stone layers that sometimes reach close to the surface (Charreau 1974, Jones and Wild 1975).

The foregoing factors acting in combination impose a significant limitation on the moisture-holding capacity of these soils. Estimates range from 25 to 50 mm (Gigou 1973, Le Buanec 1975). The buffering effect of the soils with respect to breaks in the rains of a week to 10 days is limited. *Drought*, as an ecophysiological phenomenon, is thus made almost synonymous with *dry spell*, a meteorological occurrence. In view of the well-documented effects of drought at various stages of growth on the morphology and ultimately on the yield of rice (Iyama and Murata 1961, Yoshida 1975, Tanaka 1976), the very close relationship between drought and dry spell in West Africa must be considered a major production constraint on dryland rice.

Evapotranspiration. The moderate to high evaporative demand coupled with rice's relatively shallow rooting system accentuates the closeness between dry spells and drought in West Africa (Le Buanec 1975, Nicou et al 1970). The water requirement for rice ranges from 5 to 6 mm/day (Ridders 1972, Chabrolin 1977). Mean maximum evapotranspiration values of 4-4.5 mm/day were recorded for the dryland variety OS6 grown on 2 different soils at IITA (Lawson and Alluri 1979). If a 4-6 mm/day water requirement could be presumed along a south-north transect for the region, the average figure of 5 mm/day suggested by Cocheme (1971) for the area as a whole seems realistic for the cropping season. Given the low moisture storage capacity of the soil, risk of drought during the growing season becomes higher for a crop forced to satisfy its moisture demand from the top 20 cm or so of the soil (Hasebe et al 1963, Moormann and Veldkamp 1978).

Solar radiation

Detailed agronomic and physiological studies have clearly established that in general the level of solar radiation in the wetter parts of the tropics constitutes a limiting factor to rice yield (Rao and Deb 1974, Tanaka et al 1966). The reproductive and ripening phases of growth have been identified as particularly sensitive to low light intensity

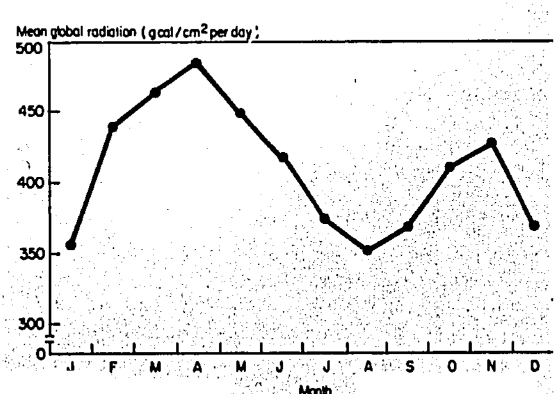
(Yoshida and Parao 1976, Wada et al 1973, Tanaka 1976).

Global radiation. Global radiation over the region is intimately tied to the pattern of cloudiness (Fig.3,4; Lawson 1975). Values generally increase from south to north (Table 1) in inverse relation to the rainfall pattern. The average is about 480 cal/cm^2 daily early in the cropping season in the north (Jun-Jul) and 420 cal/cm^2 daily in the south (Mar-Apr). During the later growth stages, it drops to 450 cal/cm^2 daily (Aug-Sep) in the far north and to 350 cal/cm^2 daily (Sep-Oct) in the far south.

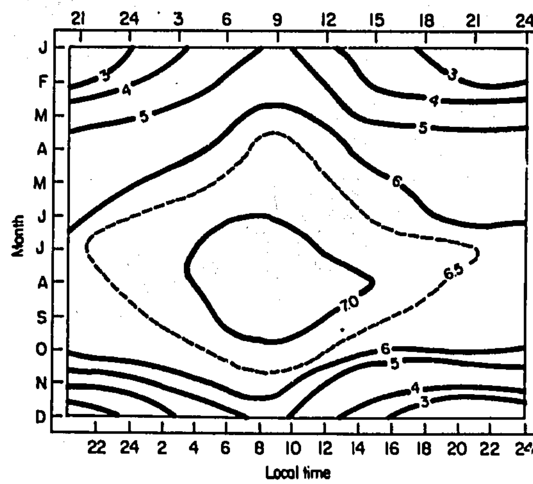
Evidence from Yoshida and Parao (1976), showing that the numbers of spikelets increase with increases in solar radiation up to 500 cal/cm^2 per day, implies that the prevailing light is at best potentially limiting in the north. The constraint seems much more pronounced both in the wet coastal zone and the south central area of bimodal rainfall (Fig.5). The rapid decline in solar radiation in this area is coincident with what would be the most sensitive period of a first season rice crop.

The limiting role of poor light on rice production may not in fact come into play under the low to moderate yields that obtain at present (Yoshida and Parao 1976, Posner 1978). However, the need to improve these yields must take cognizance of low radiation as a constraint, particularly when water and nutrient requirements have been improved.

Photoperiod response. The general trend toward adopting photoperiod-insensitive varieties considerably reduces the importance of light duration and offers flexibility in growing the crop. The use of sensitive varieties in areas of erratic rainy season to ensure



3. Monthly mean global radiation. International Institute of Tropical Agriculture, Ibadan, Nigeria, 1972–75.

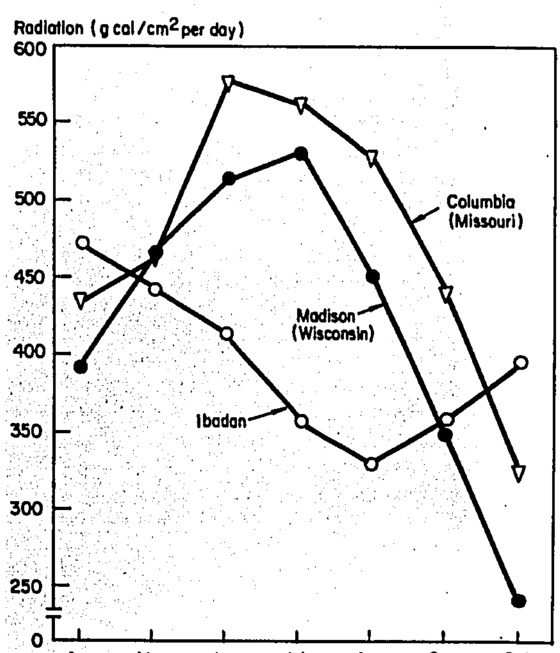


4. 18-year average mean cloud amounts at Ibadan Aerodrome, 1949–66 (values in octas).

moisture availability should be further investigated (Chang and Oka 1976). With the dryland rice cropping season tied to the rainy season, the maximum difference in day length is roughly 1 hour in the north and 30 minutes in the south.

Temperature

Daytime temperature distribution follows the pattern of global radiation, decreasing from the drier north to the wetter south.



5. Global radiation at Ibadan (7°26'N, 3°54'E), Columbia, Missouri (38°58'N, 92°20'W), and Madison, Wisconsin (43°15'N, 89°31'W) (based on observations at International Institute of Tropical Agriculture and data from Court 1974).

Table 1. Mean monthly global radiation for selected months and stations in West Africa.[a]

Station	Location		Global radiation (cal/cm^2 per day)[a]				
	Latitude	Longitude	Apr	Jul	Aug	Sep	Oct
Tabacounda	13°56'N	13°41'W	553	464	405	431	435
Mopti	14°30'N	4°12'W	500	489	463	474	438
Zinder	13°48'N	9°00'E	534	516	448	482	491
Daru	8°00'N	10°51'W	490	394	304	358	415
Markurdi	7°41'N	8°37'E	487	425	341	391	426
Bouake	7°41'N	5°02'W	429	377	317	367	398
Ibadan	7°24'N	3°53'E	434	384	335	367	401
Monrovia	6°18'N	10°48'W	443	354	298	332	395
Port Harcourt	4°46'N	7°01'E	397	314	294	322	357

[a]Computed from sunshine hours data (Lawson 1969.)

Air temperature. Air temperatures re high early in the cropping season in oth north and south (Table 2). In most ases they fall outside the 20°-30°C ange recommended for maximum photosynhesis in most C_3 plants (Monteith 1977). owever, there appears to be sufficient arietal differences in the rice plant and a fair degree of interaction between temperature and other environmental factors with respect to rice's different growth stages to disallow the specification of a set of cardinal values. Evidence of this is the 25°-35°C range reported by Osada (1964) as optimum for photosynthesis in indica rice varieties. In other studies

Table 2. Mean maximum and minimum temperatures at representative stations for selected months.[a]

Station	Location		Temperatures (°C)					
			Maximum			Minimum		
	Latitude	Longitude	Apr	Jul	Oct	Apr	Jul	Oct
Tabacounda	13°56'N	13°41'W	41.0	32.4	34.2	23.0	22.6	21.8
Mopti	14°30'N	4°12'W	39.8	33.9	33.7	22.6	23.5	23.6
Zinder	13°48'N	9°00'E	40.6	33.9	37.8	23.9	22.1	21.7
Daru	8°00'N	10°51'W	33.3	28.9	31.7	22.2	21.7	21.7
Markurdi	7°41'N	8°37'E	35.0	29.4	31.1	24.4	22.2	21.7
Bouake	7°41'N	5°02'W	34.2	29.8	31.2	21.9	20.8	20.9
Ibadan	7°24'N	3°53'E	32.8	27.8	30.0	22.8	21.1	22.2
Monrovia	6°18'N	10°48'W	30.6	26.3	28.3	22.8	22.2	22.2
Port Harcourt	4°46'N	7°01'E	31.7	28.9	29.4	22.8	21.7	21.7

[a]Compiled from A. N. Lebedev, ed.

different rice varieties showed almost no response to temperature between 18° and 33°C under high light intensity over their growing period (Yamada et al 1955, Ormrod 1961).

In spite of the apparent plasticity of the crop, certain generalizations can still be made with respect to its performance in the West African temperature regimes. The high daytime temperatures (Table 2) should induce a faster rate of growth and development, reducing vegetative growth and shortening the grain-filling period (Yoshida and Parao 1976).

The reduction in overall dry matter produced is bound to be accentuated by the high night temperatures as a result of induced higher rates of respiration and reduced net photosynthesis. These high temperatures, therefore, constitute a performance constraint on dryland rice in the region.

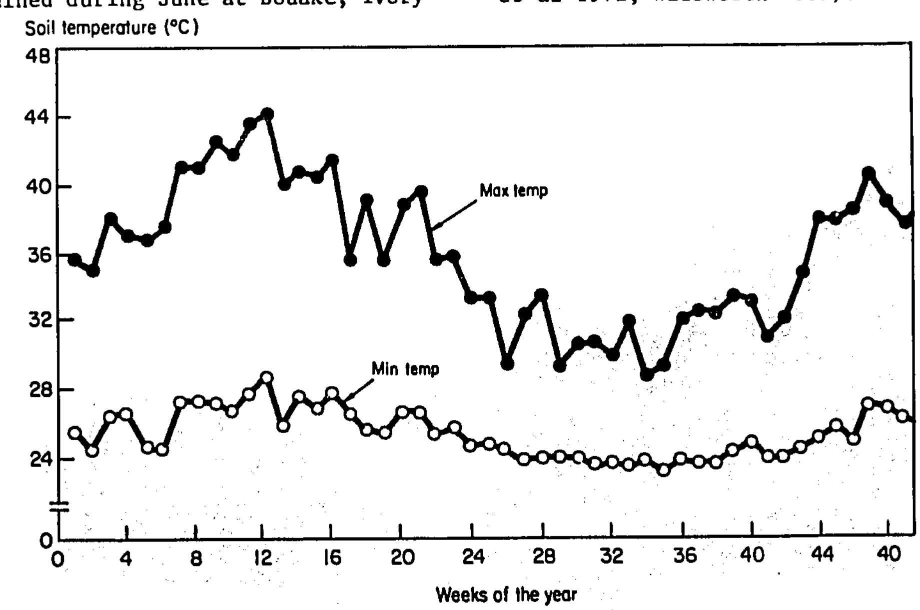
Soil temperature. Soil temperatures influence all the main physiological and morphological processes of rice. Tanaka and Munakata (1970) reported a decrease in photosynthesis at root temperatures exceeding 30°C and up to 40°C when leaf temperature remained at 30°C. Nishiyama (1976) gave optimum temperature ranges of 18-40°C for germination, 25-30°C for seedling emergence, and 25-28°C for rooting.

There is sufficient evidence that most areas of West Africa experience higher soil temperatures. An average maximum value of 47°C at 1 cm under rice was obtained during June at Bouake, Ivory Coast (Kalms, personal communication). Observations at Kpong, Ghana, for 13 years gave average mid-afternoon (1500 LST) values of 34.1°C and 33.7°C at 5 cm for the first 2 months of the cropping season (Apr, May). A typical annual trend in soil temperature is presented in Figure 6, based on observations on bare soil at IITA. It is believed typical of the bimodal rainfall areas. In all the above cases, values on specific days within the averaging period certainly reach well beyond the mean. Such would be the case particularly after a succession of rainless days. It is reasonable to deduce that these temperatures contribute to poor crop performance and cannot be ignored.

Wind

Average wind speeds for various stations within the tropics mask the contrast in the course of the same day, between the considerable period of near dead calm followed at times by violent gusts associated with squall lines or well-developed individual thunderstorms. These are characteristic of the West African region.

The turbulence in crop canopies is restricted during periods of calm. The fluxes of various properties, among them heat, moisture, and carbon dioxide, are consequently limited, and photosynthesis is conceivably reduced as boundary layer resistance and leaf temperatures increase while carbon dioxide decreases (Yabuki et al 1972, Wadsworth 1959).



6. Soil temperature at 5 cm. International Institute of Tropical Agriculture, 1977.

The impact of strong winds, on the other hand, is mechanical. Their passage is usually marked by variable degrees of lodging or by breakage of plant parts. Most upland rice varieties tend to be tall and are prone to such damage. Shorter plants would substantially remove this constraint.

Indirect factors

The indirect influences of the foregoing factors, through complexes such as diseases and nutrient availability, are subjects in their own right and cannot be adequately covered here. Their impact in further reducing the yield potential possible under the above conditions cannot, however, be underestimated.

SUMMARY AND CONCLUSION

For high performance, dryland rice requires adequate *and* regular moisture, high levels of insolation, particularly in the reproductive and ripening phases of growth, and moderate temperatures and wind regimes. In terms of these requirements, the agroclimatic conditions in West Africa must be considered less than ideal.

Rainfall variability, limited moisture holding capacity of most of the soils, and moderate to high evaporative demand in combination give rise to occasional moisture deficits during the growing season. The shallow rooting system of the crop does not prove helpful in this regard. Even the wetter areas with more reliable moisture regimes are plagued by low radiation resulting from cloudiness.

Soil and air temperatures are in most cases too high for optimum dry matter production, and occasional squalls induce lodging.

These environmental factors need to be recognized and a judicious selection of sites, varieties, and cultural practices made if significant improvement in dryland rice production in the region is to be achieved.

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The agroclimatic classification of rice-growing environments in Indonesia

L. R. Oldeman

The agroclimatic classification in Indonesia is based on the length of the growing period for bunded rice and upland crops. Since bunded rice is the main food crop in the region, the agroclimatic zones are classified according to the length of the wet period (number of consecutive months with more than 200 mm rainfall/month). Five main zones are defined and each is divided into 5 subclasses according to the length of the dry period (number of consecutive months with less than 100 mm rainfall/month). Using long-term monthly rainfall records and monthly rainfall maps, a total of 12 agroclimatic zones have been delineated on Java, Sulawesi, and Sumatra (Kalimantan in progress). They are the first step for the agroclimatic suitability classification of Southeast Asia carried out under the supervision of the FAO-Unesco-WMO Interagency Group of Agricultural Biometeorology.

Many attempts have been made to classify and delineate on maps the earth environment of Indonesia, but only recently has the climatic environment been described in terms related to agriculture, despite the fact that the climate of Indonesia is extremely well documented. Climate varies from place to place, and also from month to month. Cropping patterns also vary with place and time and are strongly related to the climate patterns.

The first climatic classification based on rainfall patterns in Indonesia, proposed by Mohr (1933), was based on the total number of dry and wet months. A month was wet when rainfall exceeded evaporation or when rainfall was more than 100 mm, a dry month received less than 60 mm rainfall. Boerema (1941) who arranged rainfall profiles had 69 types for Java and Bali alone. In 1951, Smith and Ferguson simplified the rainfall patterns by introducing a Q factor, which is the ratio between the average numbers of wet and dry months. They delineated 8 zones, using 1.5 dry-month increments: zone A has 0-1.5 dry months (Q = 0.14), zone B has 1.6-3 dry months (Q = 0.33), etc.

During a workshop at the International Rice Research Institute in 1973, an attempt was made to identify macro soil and climatic zones that together approximate a representative spectrum of the rice-growing physical environment of Southeast Asia (IRRI 1974). Agroclimatic zones were based on the amount of monthly rainfall and the length of consecutive wet months (a month with at least 200 mm precipitation). Each zone was subdivided according to the presence of a dry period of at least 2 consecutive months, an additional rainfall peak during the remainder of the year, and/or a sharp end to the rainy season. The classification produced eight agroclimatic zones (Oldeman 1974). As a follow up, agroclimatic maps have been developed and published for Indonesia.

After a short description of the Indonesian climate with emphasis on rainfall distribution, the crop water requirements for rice and upland crops will be discussed. This discussion leads to a classification of agroclimatic zones in Indonesia, and a description of the agroclimatic maps of Java, Sulawesi, and Sumatra. Finally, a few remarks are made regarding the follow-up action needed to complement the maps.

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THE CLIMATE OF INDONESIA

Rainfall

Indonesia is located between 5° north and 10° south of the equator. Bounded by the Indian Ocean on the west and the Pacific Ocean and South China Sea on the east, Indonesia is between the Eurasian continent in the north and Australia in the south. The oceans continuously supply humid air through evaporation and the land masses influence its flow. The northeast trade winds prevail north of the equator and southeast trade winds south of the equator.

From October through March the northeast winds cross the equator and arrive in Indonesia as northwest monsoons. They bring heavy rains first in the northern parts, and later also in the south and the southeast. From April to September, southeast trade winds originating from Australia prevail over Indonesia but carry less moisture. The dry air arrives first in south and southeast Indonesia but eventually penetrates to the north. In general, the climate is characterized by short dry seasons and long rainy seasons near the equator with a gradual lengthening of the dry season towards the south and southeast. Compare Pontianak (0°01'S), Kota Bumi (4°40'S), Serang (6°11'S), Pasuruan (7°40'S), and Kupang (10°10'S) in Table 1.

North of the equator the southwest monsoon penetrates Sumatra from the Indian Ocean and causes increased rainfall in May and June. The dry air from the Eurasian continent reaches north Sumatra around January-February and leads to a bimodal rainfall distribution (See Kutacane, Lhok Seumawe, and Kota Mobagu in Table 1).

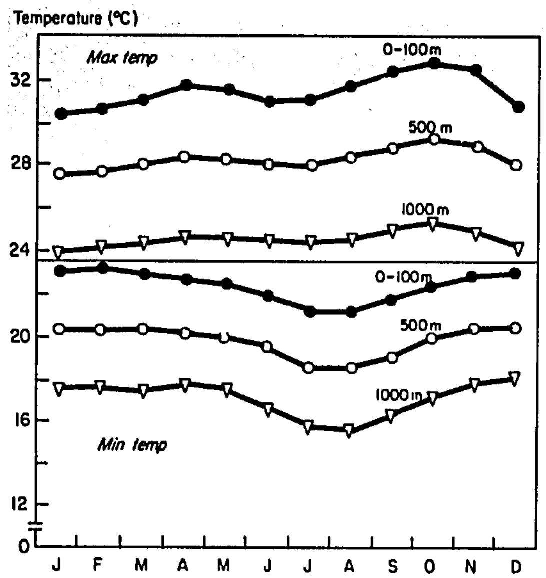
Orographic rainfall is caused when humid air is pushed upward against mountain chains. The humid air rises, cools, and condenses into heavy rainfall. If a mountain chain, such as the Bukit Barisan mountain chain in Sumatra, is perpendicular to the monsoon direction, heavy precipitation is expected on the windward side, while the leeward side remains relatively dry (compare Padang on the windward and Singkarak on the leeward sides). Mountain chains that parallel the coastline enhance local air circulation. At night, cool air descends towards the coast. During the day, humid air from the sea is blown towards the mountains, leading to heavy rainfall mainly in the afternoon. Therefore, rainfall increases rapidly from the coastline towards the mountains (compare Jakarta and Bogor).

Annual precipitation in Indonesia

Table 1. Monthly precipitation for locations in Indonesia.[a]

Location	Precipitation (mm)												Annual total	Zone
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Pontianak	277	208	242	278	282	222	164	204	228	365	388	322	3180	
Kota Bumi	364	264	316	228	165	127	100	83	107	146	181	342	2423	
Serang	265	218	180	149	138	119	81	68	74	106	178	218	1794	
Pasuruan	259	271	222	133	90	62	22	5	6	16	59	171	1316	
Kupang	386	347	234	65	30	10	5	2	2	17	83	232	1413	
Kutacane	170	116	198	249	256	166	113	161	219	329	311	272	2559	
Lhok Seumawe	199	61	75	89	108	84	82	93	111	163	193	262	1520	
Kota Mobagu	173	144	169	220	252	187	138	96	104	152	217	171	2023	
Padang	352	257	309	268	325	297	267	349	411	510	520	488	4453	
Singkarak	184	123	158	182	119	72	52	100	148	166	152	205	1661	
Jakarta	300	299	210	147	113	96	63	42	66	111	142	204	1793	
Bogor	422	391	393	408	364	268	237	239	322	435	394	357	4230	
Blang Rakal	260	209	317	420	233	110	109	166	247	335	376	321		B1
Sidikalang	223	169	266	275	170	104	106	146	205	257	293	224		B1'
Bengkalis	178	126	201	245	194	129	117	162	229	273	333	282		D1'
Medan	144	84	107	133	174	131	133	173	214	268	239	215		D1

[a]Underscoring identifies areas with bimodal rainfall patterns.



1. Seasonal fluctuation of the maximum and minimum temperatures at various altitudes.

varies from 530 mm (Palu, Sulawesi) to 6,830 mm (Krangan, Java). The rainfall patterns discussed above serve to illustrate the precipitation variability. In Table 1, the monthly rainfall is given for the locations described (Braak 1939; Boerema 1941; Berlage 1949; Oldeman 1975, 1977, 1979).

Temperature

Because Indonesia is located near the equator, the climate is typically isothermal. Seasonal variations in air temperature are small and mainly related to elevation above sea level. The maximum temperature decreases 0.6°C/100 m; the minimum temperature decreases 0.5°C/100 m. Based on 60 locations with temperature records, the relation between the annual temperature and elevation is (Oldeman 1977):

$$t_{max} = 31.3 - 0.006\ x$$
$$t_{min} = 22.8 - 0.005\ x$$

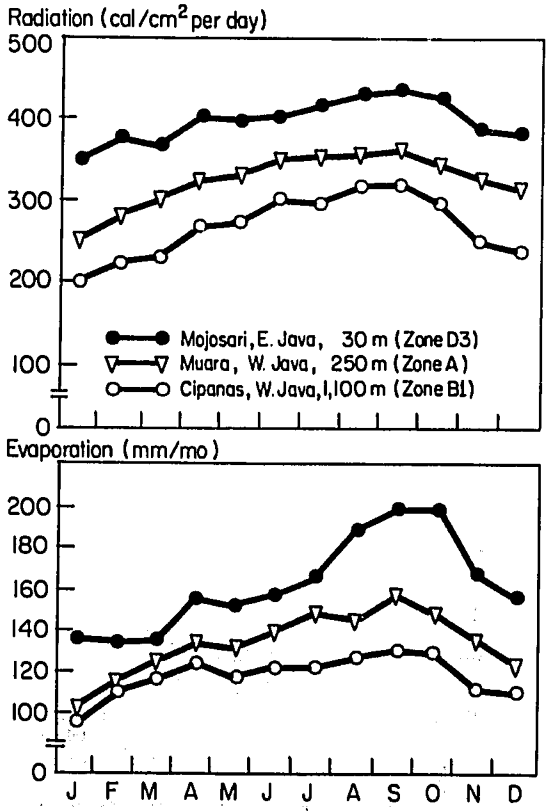
where, t is °Celsius and x is meters above sea level. The maximum temperature is slightly lower than the mean maximum in December and January and reaches high values around October (end of the dry season). The minimum temperature is a few degrees lower than the mean in July and August, particularly in south and southeast Indonesia. Figure 1 illustrates these monthly patterns for locations at various altitudes.

Radiation and evaporation

Low radiation intensities and low evaporation values occur during the wet season and values increase during the dry season. Because of increased cloud cover, radiation is much lower in mountainous areas than in coastal regions or inland plains (Fig. 2).

Relative humidity and wind speed

Minimum monthly variations in relative humidity during the wet season are between 75% and 85%. During the dry season these values may drop below 60% at low elevations. Wind seldom causes severe damage to crops. Wind speeds are generally very low at night and increase during the day. Wind velocities in Jakarta during the day are between 2.5 m/second in the wet season and 3.5 m/second in the dry.



2. Seasonal fluctuation of radiation and evaporation at three locations.

CROP-WATER REQUIREMENTS

Doorenbos and Pruitt (1977) define crop-water requirements as "the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environments." In the humid tropics, where temperature is generally not a limiting factor, the duration of the cropping season depends on rainfall except in irrigated areas. Farmers in dryland regions must adapt their crops or cropping patterns to the existing precipitation environment. The cropping patterns are often rice-based. In order to describe the various agroclimatic zones in relation to rice-based cropping patterns, water requirements should be determined for rice and for dryland crops. These requirements should then be related to precipitation. The values of field evaporation to reference (potential) ET have been generally used as crop coefficient in planning field irrigation.

Crop evapotranspiration

Crop evapotranspiration (ET crop) is determined by the climatic environment and the specific crop characteristics. In order to calculate ET crop, the reference (potential) crop evapotranspiration (ETO) should be determined (Doorenbos and Pruitt 1977). Under conditions of weak to moderate wind speed and medium to high mean relative humidity, ETO is determined mainly by radiation intensity. Crop coefficients (Kc) relate ETO to ET crop: ET crop = Kc(ETO). The value of Kc depends on the crop species and the phenological stage of the crop. It is obvious that less water is required at early growth stages for upland crops than during the midseason stage; often, lower amounts of water are needed during the ripening phase. The Kc for most upland crops is between 0.3 and 0.6 during the first month; the Kc for bunded rice is about 1.1 throughout the crop cycle. In general, upland crops during the first month require only half the amount of water required at the full canopy stage. In Table 2, the ET crop is estimated for corn, legumes (soybean and peanuts), and rice during the various phenological stages in both wet and dry seasons. At the end of the development stage and early in the midseason stage, upland crops require around 140 mm water/month during the dry season. Rice requires around 160 mm water/month during the dry season and 110 mm/month during the wet season. These amounts could be defined as consumptive use by the crop.

The total water requirement also depends on the water losses due to percolation in bunded rice and on the soil's water-holding capacity in upland crops. Rice farmers traditionally cultivate their rice soils under wet conditions which leads to the formation of low permeable subsurface horizons and reduces the rate of percolation. For the alluvial soils on Java, NEDECO (1973) recommends 1 mm water/day. This suggests a water requirement for rice that varies between 140 mm/month during the wet season and 190 mm/month during the dry. The soil's water-holding capacity varies from 50 to 100 mm for most tropical soils according to values quoted in the literature. Assuming that this water is available to the crop at the midseason stage, about 60 mm/month of additional water should fulfill the total water requirements for upland crops.

Table 2. Crop water requirements for corn, legumes, and rice during 4 phenological growth stages in the wet and dry seasons.[a]

Growth Stage	Corn			Legumes			Rice		
	Kc	Water (mm/mo)		Kc	Water (mm/mo)		Kc	Water (mm/mo)	
		WS	DS		WS	DS		WS	DS
Initial	0.5	45	67	0.5	45	67	1.1	99	148
Development	0.8	72	108	0.75	67	101	1.1	99	148
Midseason	1.05	94	142	0.95	85	128	1.15	104	155
Ripening	0.75	67	101	0.65	58	88	1	90	135

[a]Reference (potential) evapotranspiration is 3.0 for the wet (WS) and 4.5 for the dry (DS) season for each crop. Kc coefficients from Doorenbos and Pruitt (1977).

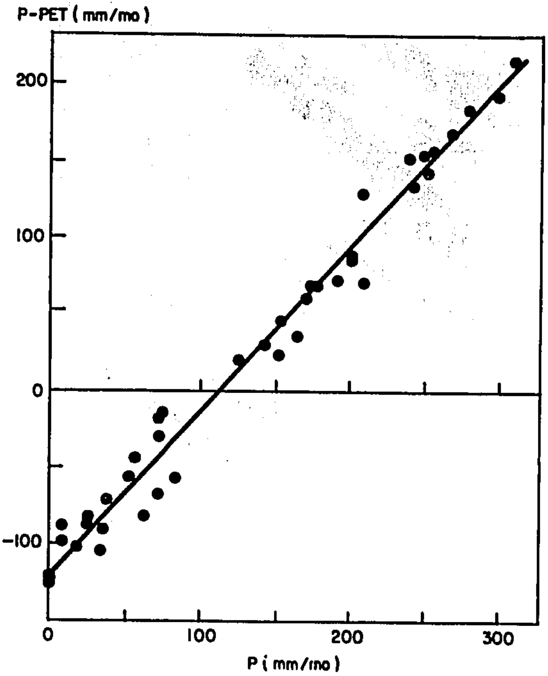
Precipitation requirements

Total crop water requirements must be transformed into precipitation requirements where precipitation is the only water source. Farmers are interested in amounts of rainfall that can be expected during a certain period in, for example, 3 out of 4 years. The relationship between long-term mean monthly rainfall (x) and dependable monthly rainfall at 75% probability (y) is highly significant: $y = 0.82\ x - 30$ (Oldeman 1977). By substituting in this equation the dependable rainfall for the total water requirement, we can express for rainfed areas the water requirement in millimeters of rainfall. For a crop of bunded rice grown in the wet season, the long-term mean monthly rainfall should be at least 200 mm/month (140 mm = 0.82 x - 30). For upland crops, it should be at least 100 mm/month (60 mm = 0.82 x - 30).

The growing period

As discussed earlier, the amount of water required to sustain the growth of germinating dryland crops (initial phase) is around half the full rate of evapotranspiration required during the midseason stage. This period is generally not longer than 1 month. Because data on evapotranspiration are scarce compared to data on precipitation, the growing period should, if possible, be expressed in terms of rainfall. Figure 3 shows the relationship between precipitation (P) and the difference between precipitation and evapotranspiration (P - PET), using data from a number of locations in the humid tropics. Precipitation of more than 115 mm/month exceeds full evapotranspiration. Precipitation of more than 60 mm/month exceeds half the evapotranspiration. The growing period can be defined as the continuous period (in months) when precipitation is more than 100 mm/month, plus a period of 1 month at the onset of the growing period when precipitation is at least 50 mm, plus a period of not more than 1 month at the end of the growing season to allow evapotranspiration of an assumed 100 mm water stored in the soil profile. This amount of precipitation meets the crop demands.

The growing period thus defined may exhibit a period when precipitation is more than 200 mm/month. For rice-based cropping patterns, it is also important to define the wet period -- the number of consecutive months when precipitation is more than 200 mm/month.

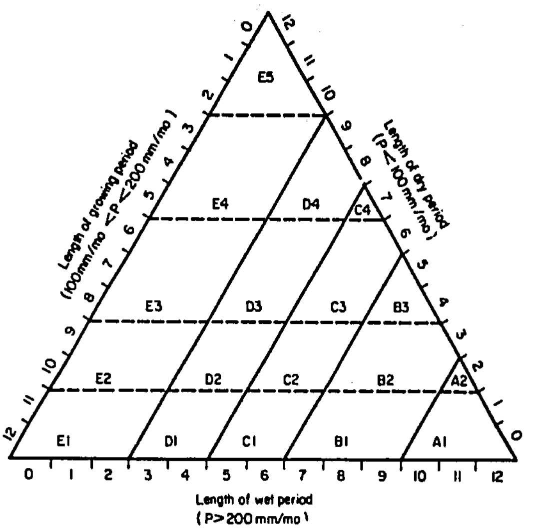


3. Relation between monthly mean precipitation (P) and the difference between monthly precipitation and monthly evapotranspiration (P-PET) (data from Bangkok, Mojosari, Los Baños, and Aran).

CLASSIFICATION OF AGROCLIMATIC ZONES

The classification of agroclimatic zones for Indonesia is based on the precipitation requirements for rice and upland crops, and on the number of consecutive wet and dry months inherent in the growing period (= 12 - length of the dry period). These periods may include not more than 1 month when precipitation is between 100 and 200 mm. Rainfed rice requires a minimum of 3 consecutive wet months to cultivate 1 crop, at least 5 months for 2 crops provided the first is sown prior to the onset of the rains, at least 7 months for 2 crops of transplanted rice in sequence, and at least 10 months for year-round cultivation. Therefore, there are five main agroclimatic zones:

Zone A: more than 9 consecutive wet months.
Zone B: 7-9 consecutive wet months.
Zone C: 5-6 consecutive wet months.
Zone D: 3-4 consecutive wet months.
Zone E: less than 3 consecutive wet months.



4. System of agroclimatic classification.

The main agroclimatic zones are subdivided according to the number of consecutive dry months. If this period is less than 2 months, year-round cultivation of food crops is possible. A dry period of 2 to 3 months requires careful planning for year-round cultivation. A fallow period is unavoidable if the dry season lasts 4 to 6 months, but 2 crops in sequence are possible. A dry season of 7-9 months, or a growing period of 3 to 5 months allows cultivation of only 1 food crop. If the dry period is more than 9 consecutive months, the area is not suitable for food crops without irrigation. The complete classification system has a total of 18 agroclimatic zones (Fig. 4). In addition, a number of specific zones have been distinguished. Bimodal rainfall patterns prevail in large parts of Indonesia, north of the equator. If the wet period is interrupted by 2 or more months with rainfall between 100 and 200 mm/month, the zone is classified according to the length of the longest wet period. The bimodality between zone B and D can be seen in Table 1. While Blang Rakal with 9 consecutive wet months is a typical rainfall profile for zone B1, and Medan with 4 consecutive wet months is typical for D1, Sidikalang differs from Bengkalis only because of the precipitation in January. The consecutive wet period in Sidikalang lasts from September until April with February the only month that has less than 200 mm rainfall. In Bengkalis, the main wet period is from September to December; a secondary 2-month wet period lasts from March to April.

A second distinction is made for areas that receive more than 400 mm/month for at least 2 consecutive months. These areas may suffer floods.

AGROCLIMATIC MAPS OF INDONESIA

Agroclimatic maps based on the classification criteria presented have been prepared for Java, Sulawesi, and Sumatra. The map for Kalimantan is in progress. Multicolored maps have been published by the Central Research Institute for Agriculture at Bogor within the framework of the Agricultural Technical Assistance Program between Indonesia and the Netherlands (Oldeman 1975, 1977, 1979).

Mapping procedures

Two sources of precipitation information were used for delineating agroclimatic zones. The first was long-term monthly rainfall records. Berlage (1949) summarized rainfall during the period 1879-1941, and the Meteorological and Geophysics Institute of Indonesia (1969) covered 1931-60. Although the over 1,500 stations with long-term records on Java provide a network density of 11 stations/1,000 km^2, the density on the other Indonesian islands is too low (Table 3). The second source used for delineating agroclimatic zones was the

Table 3. Distribution of rainfall stations with records of various lengths and the network density on Java, Sulawesi, Sumatra, and Kalimantan.

Location	Coverage (yr) of records			Network density
	50	25-50	15-25	(stations/1000 km^2)
Java	151	1035	370	11.6
Sulawesi	18	63	35	0.67
Sumatra	42	101	267	0.87
Kalimantan	9	40	35	0.16

monthly rainfall maps prepared by Boerema (1931).

An agroclimatic map was prepared from these maps. The long-term rainfall records were used to check the validity of the zones, and scales on the final maps were adapted to the network density. A scale of 1:1,000,000 was used for Java, 1:2,500,000 for Sulawesi, and 1:3,000,000 for Sumatra. Certain parts of Sulawesi and Sumatra could, however, be mapped on a larger scale because of a higher concentration of observation points. The basic maps also show 500 and 1,000 m contour lines to indicate temperature variations, and some basic administrative features -- main roads and cities -- for easy orientation in the field. The main agroclimatic zones were given distinctive colors, and shades of the same color were used for the subzones to increase readability.

The agroclimatic maps of Java, Sulawesi, and Sumatra

The classification and delineation of agroclimatic zones makes comparison possible between Java, Sulawesi, and Sumatra. Although a total of 18 agroclimatic zones is theoretically possible, only 12 occur in mappable size: A1, B1, B2, C1, C2, C3, D1, D2, D3, E1, E2, and E3 (E4 and E5 zones are present but have not been indicated on the maps). The frequency of these zones has been calculated (Table 4,5).

Forty percent of Java has a dry period more than 4 months long; around 10% of Sulawesi has a pronounced dry season and less than 1% of Sumatra. On the other hand, around 80% of Sumatra has a wet period of 7 or more months compared to less than 30% of Java and Sulawesi.

The agroclimatic environment of Java is characterized by medium to long dry seasons which increase from western to eastern Java and from the central mountain range towards the north coast. Zone C2 and D3 are the major agroclimatic zones covering 25% and 20% of the island, respectively. Zone E is located mainly along the north and northeast coast. Although not subdivided, Zone E is characterized by at least 5 dry months. Zones A and B are located mainly in the mountainous areas, particularly in West Java. They form catchment areas for major rivers that supply water to irrigate the dry coastal plains which would otherwise not be suitable for rice.

Table 4. The frequency of the agroclimatic zones of Java, Sulawesi, and Sumatra.

Agroclimatic zone	Frequency (%) of occurrence: Java	Sulawesi	Sumatra
A1	4	1	24
B1	16	21	46
B2	7	4	1
C1	-	10	6
C2	25	11	9
C3	14	4	-
D1	-	10	10
D2	5	8	2
D3	20	4	-
E1	-	12	+
E2	-	11	2
E3	9	4	-

The agroclimatic environment of Sulawesi is characterized by short dry seasons, particularly in central and north Sulawesi, and pronounced dry seasons in the south and southeast. In contrast to Java, large areas are characterized by relatively short wet and short dry seasons that result in long growing periods. C1, D1, and E1 zones occupy over 30% of Sulawesi. In the south the wet and dry seasons are extremely pronounced, particularly on the west coast. Ujung Pandang receives more than 500 mm/month during December, January, and February and less than 100 mm/month from May until October.

The agroclimatic environment of Sumatra is characterized by long wet seasons and short dry seasons. More than 70% of the island has 7 or more consecutive wet months and less than 15% has 2 or more dry months. The Bukit Barisan mountain range extends the entire length of the island. As a consequence, the entire west coast receives over 200 mm of rain/month for 10 to 12 months. Secluded valleys and inland plains on the east side of this range receive sig-

Table 5. Summary of frequency (%) of main agroclimatic zones and subzones for Java, Sulawesi, and Sumatra.

	Frequency (%) of occurrence: A	B	C	D	E	1	2	3 (4+5)
Java	4	23	39	25	9	20	37	43
Sulawesi	1	25	25	22	27	54	34	12
Sumatra	24	46	15	12	2	86	14	+

nificantly less rainfall. The east coast has short dry seasons except in the north, where the climate is influenced by the Eurasian continental climate with a dry season from January to March. In its southern parts, the east coast climate resembles that of West Java with dry seasons from July until September. Major parts of Central and North Sumatra have bimodal rainfall with a short less rainy period in January and February and a slightly more pronounced dry season from June until September.

AGROCLIMATIC SURVEY OF SOUTHEAST ASIA

The agroclimatic classification and maps for Indonesia should be considered the first step in describing the agro-ecological zones that are suitable for cultivating major food crops. However, the maps do not inform the user on the soil and physiographic constraints which might limit optimal biomass production. Neither do they indicate present land use or actual cropping patterns.

Under the supervision of the Interagency Group on Agricultural Biometeorology, established in 1968 by FAO, Unesco, and WMO, agroclimatic surveys have been carried out in Africa, the Middle East, and South America. Consultations have recently been held with representatives of Indonesia, Malaysia, Philippines, Singapore, and Thailand to initiate an agroclimatic survey of Southeast Asia. Guidelines and instructions for the collection of relevant data on climate, soils, land use, and crop production have been prepared and working groups in each participating country have been formed to assist the Interagency group with the compilation of data. The outcome of the project will lead to regional agroclimatic suitability classification for a number of major food crops. This survey will not only complement and improve the existing agroclimatic classification, but also enable the extrapolation of agricultural technology suitable for specific agroclimatic zones to other regions within countries with the same agroclimatic characteristics. A basic understanding of the crop environment is essential for the agricultural development of a region or a nation.

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Macroclimatic aspects of rice production in Southeast Asia

S. Hardjawinata

The average annual rainfall in Southeast Asia ranges from 604 to 8837 mm. The rainfall pattern in its association with monsoon, trade wind, and local effects was discussed.

The effects of rainfall, temperature, and solar radiation on the phenological stages of rice were briefly reviewed. The format and method of acquisition of phenological rice data need to be established.

Long-range weather forecasts should be replaced by real time-weather data for yield estimates and corrective action in the operational bases.

Climatic zonation was reviewed and the development of a wet season calendar for Indonesia is recommended.

WEATHER AND CLIMATE IN SOUTHEAST ASIA

The variable weather and climate in Southeast Asia is characterized by the equatorial double rainy season, monsoon, trade winds, and local influences. Climatic variations are also due to the intensities of Walker Equatorial Circulation and Hadley Meridional Circulations. The displacement of Hadley Circulation is closely related to the sun's north-south movement with regard to the equator and the continents of Asia and Australia. The Walker Circulation is closely related to the strength of the easterly winds. These factors contribute to the displacement and intensity of the intertropical convergence zone.

This general climatic pattern influences the rice farming pattern (Fig. ia, lb). Acquisition of knowledge of this climatic pattern and the ability to forecast climatic deviation is the aim of many farmers and agriculturists.

Table 1 shows the general pattern of rainfall in various cities of Thailand, Philippines, Malaysia, and Indonesia.

In general, Thailand's rainy season is from May to October in the northern and central parts. In southern Thailand and in Malaysia it is from June to December or January.

Rainy season in the Philippines is generally from May to November or December. But in the southeastern region (Legaspi, Tacloban, and Surigao) rainfall is abundant the whole year because of the effects of the trade winds.

Indonesia is strongly influenced by the monsoon. The west monsoon generally prevails from December to March; the east monsoon prevails from June to September (Fig. 2). This is due to the enhancement effects of the westerly wind on vertical motion in the equatorial region. The highest and lowest average annual rainfall in Indonesia -- 8,837 mm and 604 mm -- is also the highest and lowest for Southeast Asia.

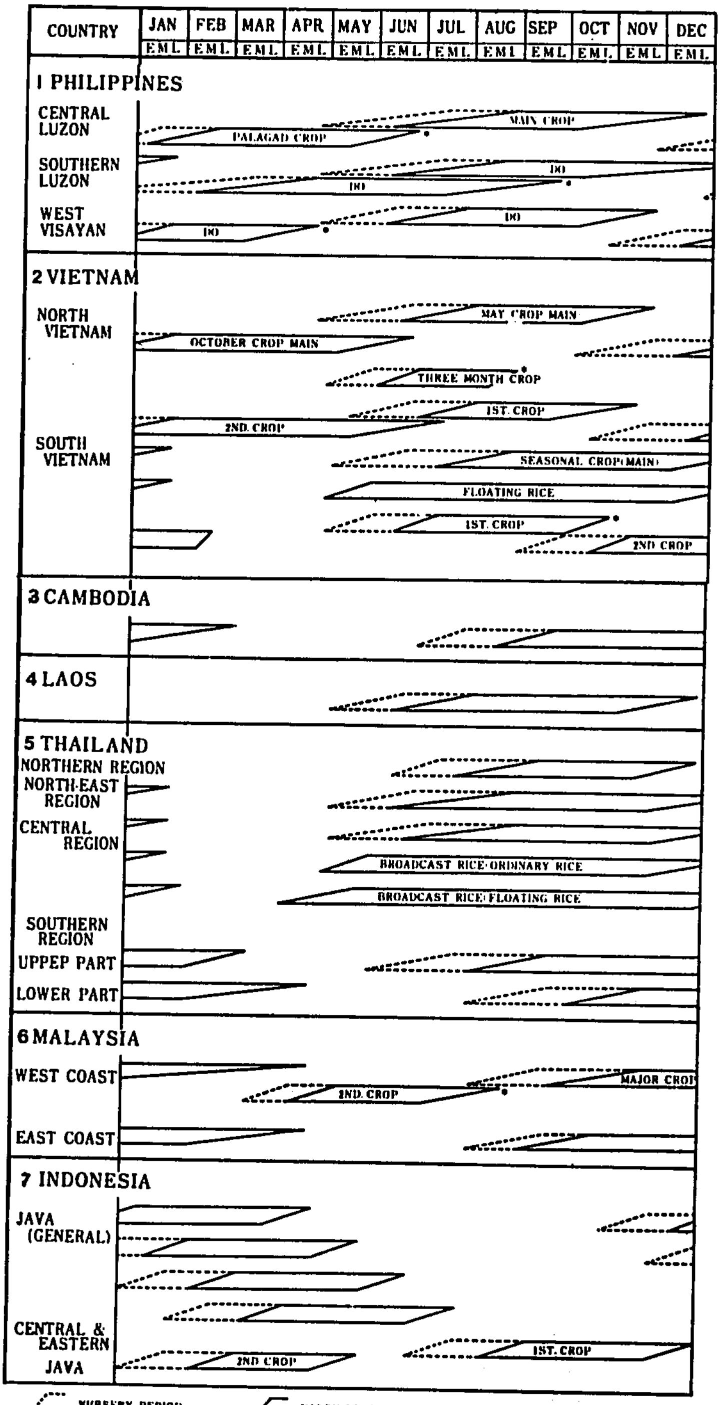
CLIMATIC ASPECTS OF RICE PRODUCTION

This discussion, will focus on the effect of various climatic factors on yield and the phenological stages of rice growth and development. These stages (Robertson 1975) are emergence, transplanting, maximum tillering, panicle primordia initiation, heading, dough stage, and maturity.

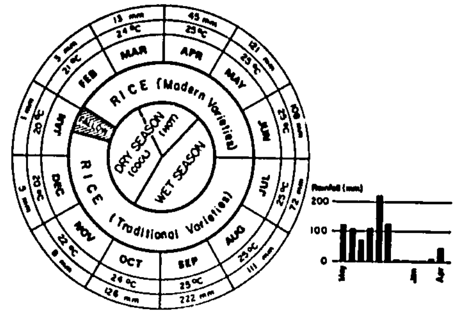
The indica rice type originated in a tropical rainy climate characterized by high temperature, low light intensity, high humidity, and abundant rainfall.

The life cycle and the climatic environment recorded in several rice-producing areas (Table 2) provide the

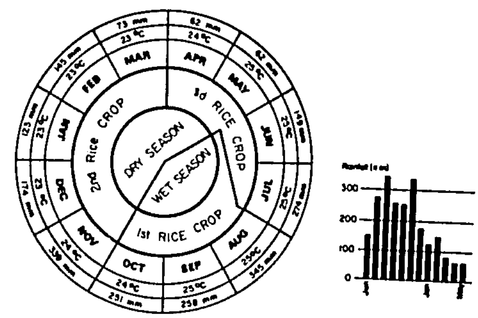
Division of Climatology, Institute of Meteorology and Geophysics, Jakarta, Indonesia.



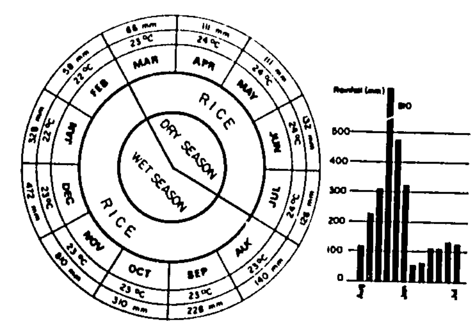
1. a) Rice seasons in Southeast Asia (Tanaka 1976).



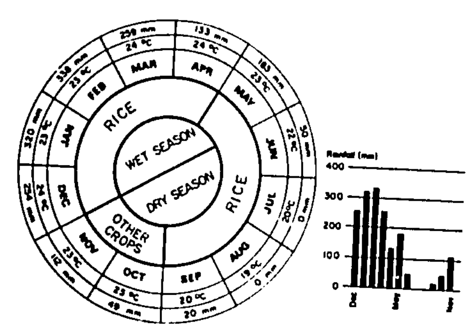
Average monthly rainfall and minimum temperature (Don Chedi, 1967-1971), Suphan Buri, Thailand.



Average monthly rainfall (Philsugin Weather Station, Ormoc City, 1967-1971) and minimum temperature (Weather Bureau, Tacloban City, 1967-1971), Leyte, Philippines.



Average monthly rainfall and minimum temperature, (Kota Bharu Meteorological Station, 1967-1971), Kelantan, Malaysia.



Average monthly rainfall and minimum temperature (Mojosari Experiment Station, 1971-1972), East Java, Indonesia.

b) Rice seasons in Southeast Asia (IRRI 1975).

Table 1. Normal monthly rainfall (mm) in Southeast Asia (CLINO 1931-60).

Country, site	Elevation (m)	Rainfall (mm) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Thailand														
Chiangmai[a]	313	7	12	15	49	144	146	188	231	289	126	39	10	1254
Udon Thani[a]	178	6	10	40	72	172	205	251	313	310	132	26	2	1539
Phitsanulok[a]	50	7	24	38	75	160	179	206	226	275	133	37	2	1362
Nakhon Sawan[b]	28	5	33	26	65	137	141	148	179	274	151	26	3	1188
Nakhon[b] Ratchasima[b]	181	7	33	45	83	157	111	132	139	244	171	37	3	1162
Bangkok[a]	12	9	29	34	89	166	171	178	191	306	255	57	7	1492
Aranyaprathet[b]	44	7	31	67	113	177	184	219	190	270	197	57	12	1524
Chanthaburi	5	21	38	67	142	352	508	557	501	558	268	81	6	3098
Prachuap Kirikhan[b]	5	33	42	48	81	114	92	97	90	111	253	172	31	1164
Chumphon[a]	3	68	70	78	122	161	161	192	172	172	318	327	192	2033
Songkhla[a]	10	157	59	58	91	119	101	94	95	105	316	576	439	2208
Malaysia														
Kota Bharu	9	211	73	112	87	142	145	155	150	191	326	617	546	2755
Kuala Lumpur	38	157	209	277	285	207	121	117	157	206	251	289	223	2499
Philippines														
Basco	11	221	131	151	90	189	254	279	422	403	412	354	322	3228
Aparri	4	146	108	51	35	106	157	165	224	307	390	386	237	2312
Dagupan	2	8	9	28	85	175	286	476	531	364	168	103	30	2263
Manila	15	18	7	6	24	110	236	253	480	271	201	129	56	1791
Legaspi	19	343	235	239	186	224	182	196	234	245	327	490	525	3426
Tacloban	21	300	191	172	129	170	150	150	130	156	197	263	314	2328
Iloilo	14	53	28	37	48	146	263	302	360	290	255	209	131	2120
Cebu[a]	42	101	70	55	70	133	186	207	175	211	191	160	144	1703
Surigao	22	589	405	398	258	184	112	195	149	197	308	415	653	3863
Zamboanga[b]	6	51	49	44	54	96	131	120	138	139	173	135	96	1226
Indonesia														
Labuhan	4	487	417	399	282	235	180	107	94	124	243	445	520	3533
Jakarta[a]	7	334	241	201	141	113	97	61	52	78	91	155	196	1760
Bogor	240	397	398	398	451	379	290	270	271	341	426	402	399	4422
Cianjur	439	291	267	295	282	168	110	88	96	163	243	291	266	2569
Baturaden	650	667	482	626	530	418	507	515	445	602	754	1669	1622	8837
Semarang	-	276	271	216	193	147	79	87	77	84	148	220	235	2033
Surabaya	5	329	278	292	209	118	90	41	18	12	43	151	256	1837
Medan	-	165	103	118	163	215	132	174	207	207	256	268	166	2174
Palembang	-	255	265	309	285	155	128	102	86	85	202	343	265	2480
Pontianak	3	272	198	207	252	281	238	179	176	255	332	345	321	3056
Banjarmasin	20	436	298	323	269	206	156	156	98	70	141	273	397	2823
Balikpapan	83	186	170	248	219	220	265	258	246	195	154	194	242	2597
Manado	22	435	351	290	229	184	154	154	130	103	138	240	375	2783
Talisse[b]	3	51	49	31	66	55	79	63	61	46	30	28	45	604
Ujung Pandang[a]	3	693	489	355	178	106	59	35	19	9	44	160	514	2661
Denpasar[a]	40	386	284	201	115	91	108	107	49	34	108	163	308	1957
Ambon	1	136	119	129	256	559	522	571	503	249	170	98	145	3457

[a]Multiple cropping is unlikely in the area without additional water supply. [b]The area is not suitable for any type of agriculture unless additional water is available. Source: Robertson 1975.

actual average climatic conditions during growth and development of indica and japonica rices in the field. Table 2 shows that indica grows in higher temperature zones with more and abundant rainfall, lower evaporation, and a lower daily percentage of bright sunshine. It also has 70% lower yield than japonica. The period from sowing to maturity is 127 days for indica and 152 for japonica. Despite the lower indica yields in the tropics, the tropical areas promise higher annual production.

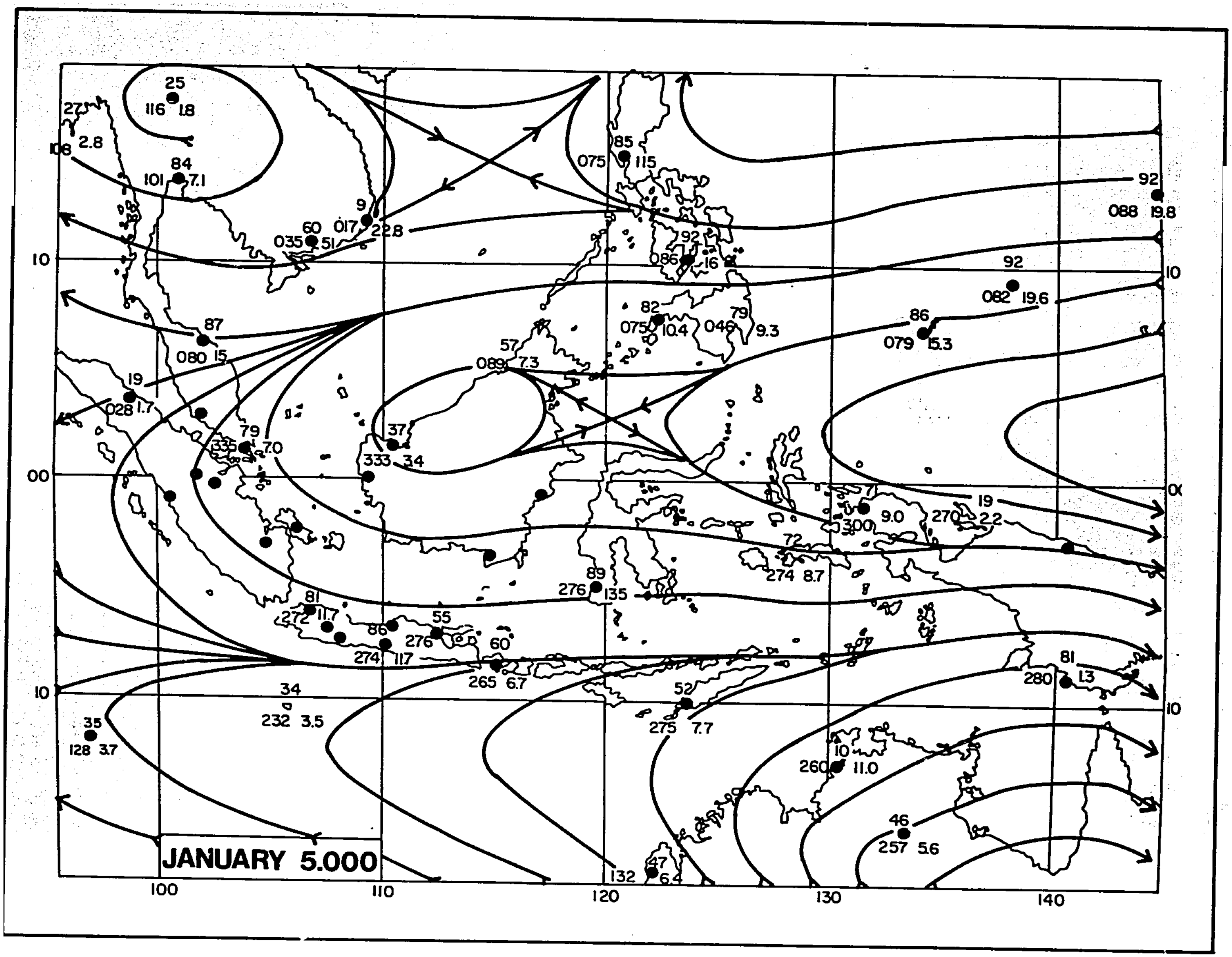
Rainfall

Rainfall pattern is the most limiting factor for rainfed rice culture in Southeast Asia.

The total water requirements for the rice crop range from 1,000 to 3,000 mm for wet-season crops, and from 700 to 2,500 mm for dry-season crops requiring 120 days from transplanting to maturity (Robertson 1975). The most critical stage for grain yield is the reproductive stage.

Temperature

Each development stage and each growth process respond differently to the same temperature, and each variety has its own character responses. Water temperature is important during the germinating and seedling stage, and soil temperature affects the nutrition of the rice plant through its effects on the chemical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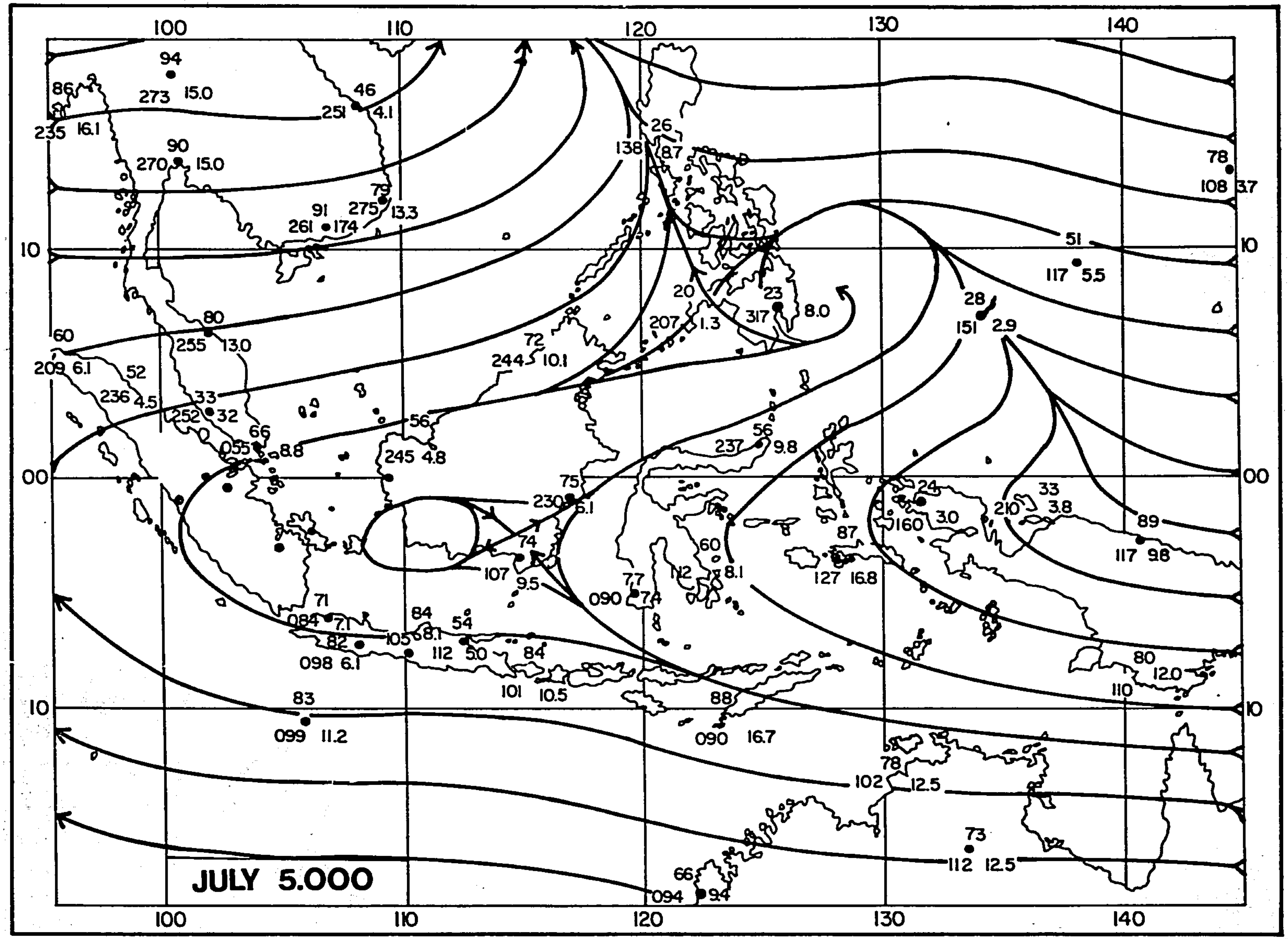


2. Mean monthly resultant wind in January and July (Sutrisno 1966).

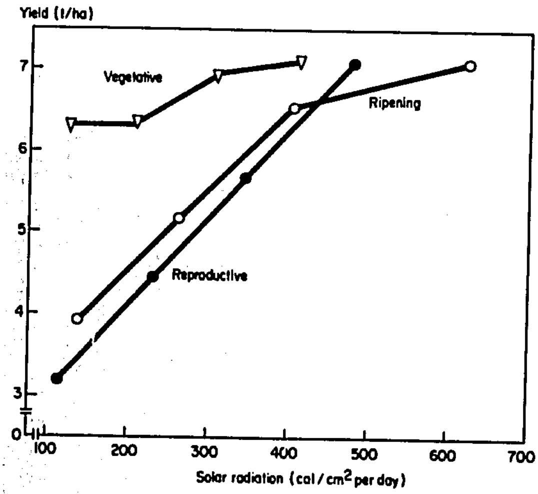
Table 2. Average climatic conditions during the life cycle of the rice plant.[a]

Climatic element	S	E	T	MT	PPI	H	DS	M
Days from S[b]								
Indica	0	5(2-14)	27(20-34)	57(34-61)	78(62-88)	96(84-115)	113(103-130)	127(118-137)
Japonica	0	11(3-25)	35(29-46)	70(31-102)	81(72-107)	108(78-125)	131(94-151)	152(112-168)
Av daily temp max (°C)								
Indica	23.0-35.0	23.8-34.9	27.4-33.8	27.7-33.5	28.3-33.4	28.8-33.3	29.3-33.7	27.5-35.2
Japonica	11.8-26.5	13.2-27.5	18.0-31.3	24.9-33.5	23.2-33.5	25.3-33.0	23.1-31.0	19.1-27.1
Av daily temp min (°C)								
Indica	12.2-24.9	13.0-25.1	16.6-25.6	17.0-25.1	20.6-24.5	20.1-24.5	19.2-25.5	17.5-24.8
Japonica	0.6-15.6	1.6-15.6	7.1-19.2	14.3-23.9	15.0-23.2	15.8-21.8	14.1-18.6	8.3-17.6
Accumulated rain (mm)								
Indica	15-360	45-390	92-920	145-1665	200-1720	235-2035	255-2190	270-2300
Japonica	40-195	65-223	110-330	135-880	150-997	180-1167	225-1340	245-1422
Evaporation from class A pan evaporimeter (mm/day)								
Indica	4.5	4.5	4.6	4.7	4.7	4.7	4.8	4.7
Japonica	3.4	4.8	6.5	6.6	6.5	5.8	4.8	4.1
Av daily global solar radiation (cal/cm^2 daily)								
Indica	289-427	290-422	317-395	369-416	368-441	361-465	354-504	336-546
Japonica	349-539	354-613	380-576	376-708	378-703	342-678	310-520	248-419
Av daily bright sunshine (%)								
Indica	20-26	19-26	12-31	17-34	19-34	24-37	26-40	27-40
Japonica	39-69	38-74	36-70	37-69	40-72	40-74	41-73	41-73
Yield[b] (kg/ha)								
Indica	3902 (2000-6500)							
Japonica	5736 (3000-8000)							

[a]S = sowing, E = emergence, T = transplanting, MT = maximum tillering, PPI = panicle primordia initiation, H = heading, DS = dough stage, M = maturity. Source: Robertson (1975) survey of rice-producing centers with indica rice from 11 stations (26°S to 30°10'N) and japonica rice from 11 stations (31°52'S to 34°55'S and 33°25'N to 43°46'). [b]Figures in parentheses indicate range.

kinetics of the soil.

The optimum temperature range (Osada 1964) is from 25° to 35°C for indica rices and from 18° to 33°C for japonica. During vegetative growth, the favorable temperature range is from 15°-18°C to 30°- 33°C (Nishiyama 1976). But within the favorable temperature range, higher temperatures, in general, favor growth and development of rice plants.



3. Effect of solar radiation at different growth stages on grain yield of IR747B2-6 (Yoshida and Parao 1976).

Solar radiation

Solar radiation during the reproductive and ripening phases (Fig. 3) has a profound influence on rice yield.

Solar radiation is not just a form of heat; its spectral bands are also important. The unsuccessful introduction of high yielding varieties at Meranti (Malaysia) and Cidahu (Indonesia) may be due to the distribution of the spectral bands.

Climatological and weather data, particularly rainfall data, are available. But, yield and phenological data are still very limited. The method and the format for acquisition of such data for rice need to be established to make agrometeorological activities possible for *operational* use and extension services.

WEATHER AND CLIMATIC INFORMATION FOR RICE PRODUCTION

Rice, the staple food of the Southeast Asian people, is produced mainly by the consuming nations. Only about 2% of world production enters into world trade

Table 3. Approximate annual world grain production and international grain trade.[a]

Commodity	Major producing countries	Production (million t)	Percentage of world grain production	Major exporting countries	Percentage of world trade	Trade as percentage of world production
Wheat	USSR	70-109		USA	30-50	
	USA	41-54		Canada	20-26	
	European Economic Community	35-41		Australia	10-15	
	Canada	14-16		European Economic Community	8-10	
				Argentina	5	
	World	310-340	26			15
Rice (paddy)	China	125-134		USA	20-27	
	India	74-87		Thailand	20-28	
	Indonesia	25-27		China	15-18	
	Bangladesh	19-25				
	World	295-310	24			2
Corn (maize)	USA	136-163		USA	68-85	
	Argentina	8-11		Argentina	10-25	
	South Africa	8-11		South Africa	8-9	
	Thailand	3		Thailand	6-8	
	World	260-300	23			11
Other coarse grains[b]	USA			USA		
	Canada			Canada		
	Argentina			Argentina		
	European Economic Community					
	World		27			4

[a]Adapted from World Cereal Grain Outlook, J.L. Leibfried 1975, paper presented to Third Farm Leader's Course, Canadian International Grains Institute, Winnipeg, Canada (after Baier 1977). [b]Includes barley, sorghum, and millet, oats, rye, and mixed grains.

(Table 3). About 85% of the 295-310 million t of the world's rice production comes from the same climatic sites. An unfavorable climatic condition in one major Asian producing area most likely will be experienced in a neighboring area. Any rice shortfall caused by adverse weather conditions will hardly be recovered from production in other regions.

Farmers, agriculturists, and government officials desire a good short- and long-range weather forecast, and warning of expected climatic changes far in advance. In view of the low reliability of such forecasts, Robertson (1975) and many other climatologists believe that real time-weather-based yield estimates are better than long-range weather forecasts.

Real time-weather-based yield estimates have been used for food crops such as wheat, by applying simulation and statistical models. Baier (1977) summarized some statistical models suitable for operational crop yield predictions (Table 4) for nonrice food crops.

Adoption of the models should be limited, depending on considerations of time and soil characteristics or geographical features. The agrometeorological data generally required for the models are: soil moisture reserve, precipitation, temperature, potential evaporation, and water vapor deficit.

A similar model for rice is provided by Das and Madnani (1971) for Madhya Maharashtra in India. To estimate rice yield in the first week of August:

$X_1 = 365 + 33.7(2)$

The first week of September:

$X_1 = 475 + 33.7(2) - 49.7(3)$

The first week of October:

$X_1 = 430 + 33.7(2) - 49.7(3) + 9.65(4)$

where, X_1 is the estimated yield in pounds per acre; x_2, the number of rainy days in July; x_3, the number of occasions of drought in August; and x_4, the number of rainy days during the last half of September. Rainy days are those with 2.5 mm or more of rainfall in 24 hours. Drought in August is determined from the number of consecutive days with less than 2.5 mm of rain and coded as follows: code 1 = 7 days; code 3 = 8 to 14 days; code 6 = 15 to 21 days; code 10 = 22 days or more.

The construction of climatic zonation and crop weather and seasonal calendars will be very useful in select-

Table 4. Summary of selected statistical models suitable for operational crop-yield predictions.[a]

Region	Crop	Agrometeorological data requirement[b] (variable)	Reference
Canada			
Prairies	S wheat	P_A; $P_{May, Jun, Jul}$	Williams and Robertson 1965
Prairies	S wheat	P_A; $(P,PE)_{May, Jun, Jul}$	Williams 1969
3 soil zones	S wheat oats, barley	P_A; $(P,PE)_{May, Jun, Jul}$	Williams et al 1975
Prairies	Barley	P_A; $(P,PE)_{May, Jun, Jul}$	Williams 1971
USA			
High Plains (Midwest)	W wheat	P_A; $(P,T)_{Apr, May, Jun, Jul}$	Thompson 1969a
Midwest (Central)	Maize	P_A; P_{Jul}; $T_{Jun, Jul, Aug}$	Thompson 1969b
Midwest	Soybean	P_A; $P_{Jul, Aug}$; $T_{Jun, Jul, Aug}$	Thompson 1970
USSR			
Chernozem	W wheat	SM_S; $(no.\ stalks/m^2)_S$; P_{May}; P_{Jun}	Ulanova 1975
	S wheat	$(SM;\ P{:}D)_{Phases}$	Ulanova 1975
	Maize	$(SM;\ T)_{LA}$	Chirkov 1969
27 soil-climate regions	W wheat	Fertilizer use, $(T,P,SM)_{Oct, Jul}$	Zabijaka 1974
	S wheat	Fertilizer use, $(T,P,SM)_{Apr-Aug}$	Zabijaka 1974
Australia	Wheat	$(P,PE)_{Weekly}$	Nix and Fitzpatrick 1969
India	Wheat	$P_{Weighted\ over\ season}$	Gangopadhyaya and Sarker 1965
Iran	Wheat	P_{Annual}	Lomas 1973
		$P_{Growing\ season}$	Hashemi 1973
Israel	Wheat	P_{Annual}	Lomas 1972
	Wheat	$P_{Weighted\ over\ season}$	Lomas and Shashoma 1973
Turkey	W wheat	$(P,T)_{Jan-Dec}$	Coffing 1973

[a]Source: Baier 1977. [b]Agrometeorological data required for generating "independent" variables in prediction equations. These variables may be used as simple, derived, exponential, or interaction terms or in any combination and selection. Variables accounting for time trend, soil characteristics, or geographical features are not considered here.
Variable:
SM = soil moisture reserves; no. stalks/m^2 = number of stalks per square meter;
P = precipitation; T = temperature; PE = potential evaporation;
D = deficit between actual and saturated water vapor.
Period:
W = winter ; S = spring; phases = phenological phases;
A = antecedent (weighted) P total for period preceding planting;
LA = period based on leaf area, observed or derived, e.g. from plant height.

ing localities with the greatest biophysical and economic advantages for any given rice variety.

Multiple cropping is important in realizing the potential annual production in the tropics, for solving the labor problem, and in offering a more favorable environment in rice-farming villages. However, continuous rice cropping may create severe pest problems.

Using mean monthly rainfall, the Working Group on the Establishment of Southeast Asian Cropping Systems Test Sites (IRRI, Philippines) has established an agroclimatic map with the following classifications:

Zone I. Areas with more than 9 consecutive wet months with more than 200 mm rainfall/month.

Zone II.1. Areas with 5 to 9 consecutive wet months and with 100 to 200 mm rainfall/month during the remainder of the year.

Zone II.2. Areas with 5 to 9 consecutive wet months and with 100 to 200 mm rainfall/month during the remainder of the year and with another minor rainfall peak.

Zone II.3. Areas with 5 to 9 consecutive wet months, including at least 2 months with less than 100 mm rainfall.

Zone II.4. Areas with 5 to 9 consecutive wet months and with a sharp ending of the rainy season, or with rainfall over 1,000 mm/month.

Zone III.1. Areas with 2 to 5 consecutive wet months but with at least 100 mm rainfall/month during the remainder of the year.

Zone III.2. Areas with 2 to 5 consecutive wet months and a pronounced dry season with at least 2 months with less than 100 mm rainfall/month.

Zone IV. Areas with less than 2 consecutive wet months.

Zone II is of major interest for multiple cropping, zone III.1 has some prospects, zone III.2 needs additional water supply, and zone IV is not suitable for any type of agriculture unless additional water is available.

Following the achievement of the working group, Oldeman issued an agroclimatic map of Java (1975) and of Sulawesi (1977). Boerema (1926) issued a detailed list of rainfall types of Indonesia, consisting of 69 rainfall regimes for Java and 84 for the other provinces (Table 5, Fig. 4a,4b). A

Table 5. Rainfall types of Indonesia (Boerema 1926).

Type[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
						Java-Madura							
1	567	573	423	380	227	126	111	133	166	297	410	599	4012
2	359	357	264	232	184	152	114	137	137	208	262	316	2722
3	413	408	380	367	246	175	145	191	176	277	319	385	3482
4*	292	302	192	141	105	80	58	42	54	97	151	206	1720
5	327	339	279	261	186	137	92	89	133	206	292	263	2604
6	381	424	391	434	308	244	190	231	269	348	422	328	3970
7	339	356	341	354	262	192	153	201	285	438	514	390	3825
8	321	325	298	341	221	138	108	142	178	329	375	337	3113
9	622	630	555	410	218	147	71	90	184	376	490	641	4434
10	350	351	347	381	224	154	93	108	178	326	436	382	3330
11	325	333	330	407	238	171	99	130	159	271	384	363	3210
12	281	320	298	298	198	129	87	102	152	247	326	281	2719
13	446	463	482	439	293	193	118	95	163	270	390	394	3746
14	234	233	250	224	138	86	56	46	81	143	236	240	1967
15	333	343	339	318	200	125	87	84	130	216	311	323	2809
16	439	434	478	490	279	199	128	135	223	421	548	438	4212
17	465	490	484	507	282	163	90	120	164	302	435	484	3986
18	276	255	236	220	196	150	124	225	305	544	417	345	3293
19	377	430	405	410	323	252	191	261	357	484	500	374	4364
20	231	243	253	273	315	289	227	362	373	673	416	277	3932
21	443	378	346	241	153	86	56	27	62	104	234	315	2445
22	684	644	519	377	225	131	63	45	89	166	331	481	3755
23	416	391	387	306	184	108	47	58	102	186	281	340	2806
24	562	541	470	336	214	137	87	87	128	237	342	459	3600
25	345	368	342	255	188	132	72	102	152	295	345	342	2938
26*	421	391	317	214	130	94	57	43	57	108	183	304	2319
27	676	758	532	435	281	208	127	116	152	252	386	511	4434
28	544	522	509	407	282	184	116	117	211	383	532	577	4384
29	457	453	494	416	297	208	151	193	302	546	577	500	4594
30	282	320	262	244	223	198	105	149	231	465	397	378	3254
31	379	383	394	279	205	156	93	82	152	346	416	458	3343
32	337	342	293	178	143	123	73	51	87	242	315	370	2554
33*	686	603	356	184	112	70	36	35	55	105	199	440	2881
34*	401	359	274	166	150	102	51	62	69	104	157	271	2166
35	416	413	255	201	135	102	62	64	105	138	219	277	2387
36	381	379	340	258	184	127	59	70	102	173	260	359	2692
37	391	384	373	267	180	126	62	50	89	245	361	424	2952
38	513	535	474	332	237	143	67	71	111	199	344	496	3522
39	365	400	313	211	144	97	39	45	65	142	249	332	2402
40*	358	326	276	195	135	77	36	57	101	165	241	297	2264
41*	273	260	216	135	108	61	32	30	39	74	139	217	1584
42*	299	299	261	191	135	73	36	34	52	110	211	265	1966
43	518	605	459	392	252	135	38	49	106	190	427	520	3691
44	285	299	242	166	106	70	39	29	36	110	186	270	1838
45	290	303	249	154	135	124	91	99	98	231	224	301	2299
46*	335	359	293	174	115	75	31	19	34	68	153	260	1916
47	455	502	396	303	201	136	52	73	76	175	281	414	3064
48	480	478	588	399	347	308	250	275	290	369	602	576	4962
49	485	587	432	253	168	90	35	28	38	85	206	341	2748
50	508	556	490	394	265	148	59	70	94	275	456	518	3833
51	330	348	288	200	121	80	44	37	42	117	235	335	2177
52*	258	275	194	107	70	46	20	9	8	24	71	170	1252
53	430	453	372	246	154	102	42	29	32	101	214	357	2532
54	311	351	302	206	165	147	98	143	115	246	274	336	2694
55	375	393	341	282	256	273	216	316	233	454	364	365	3868
56*	268	265	186	69	58	28	13	2	4	21	59	186	1159
57*	333	344	244	107	92	51	17	14	18	45	116	225	1606

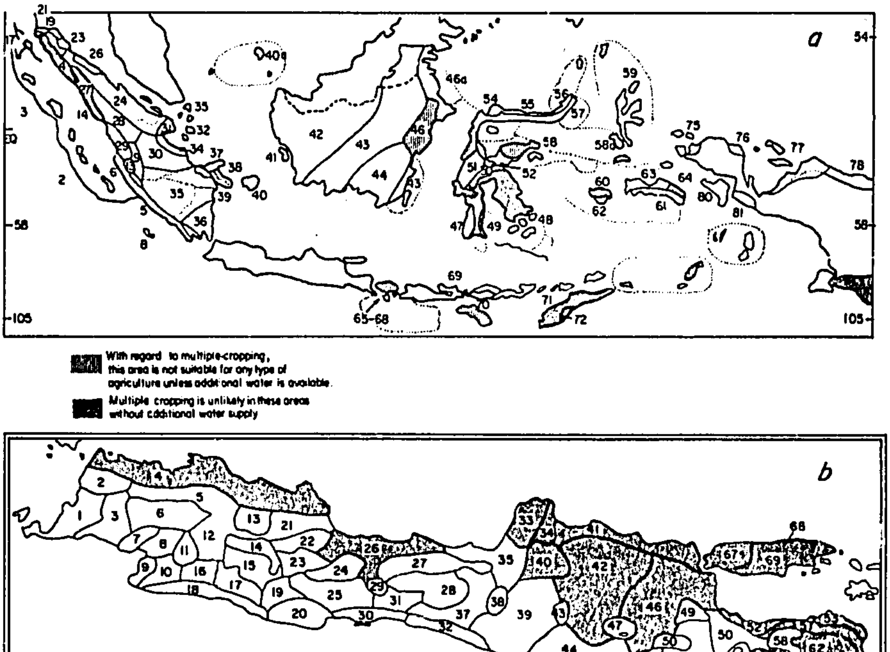
Table 5 continued

Type[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
58	569	583	484	290	189	124	52	58	82	208	348	474	3452
59	465	453	477	364	255	198	112	159	173	433	578	487	4154
60*	217	244	237	189	99	71	35	30	28	105	190	239	1634
61*	328	335	311	183	121	72	29	39	48	155	257	353	2231
62*	373	377	316	178	131	72	37	37	44	108	214	317	2204
63*	311	351	310	165	111	68	42	36	23	37	129	244	1827
64	582	599	489	209	250	166	128	172	70	85	186	395	3331
65	435	415	368	217	279	259	236	295	160	197	256	364	3481
66*	294	315	251	126	150	130	106	127	75	123	158	241	2096
67*	312	290	247	188	149	71	29	37	42	93	195	235	1888
68**	172	185	131	104	72	43	11	12	8	50	98	155	1041
69	261	247	214	148	108	59	22	10	14	59	133	209	1484
							Other Indonesian provinces						
1	492	521	321	266	207	258	238	241	338	518	619	583	4602
2	333	281	280	316	219	248	291	298	394	433	453	421	3967
3	223	191	231	282	253	184	245	274	331	381	346	292	3233
4*	246	229	172	224	158	142	146	207	226	271	291	235	2587
5	270	265	243	234	210	195	183	234	286	339	369	329	3157
6	291	247	251	270	170	157	170	193	292	332	378	339	3090
7	518	411	444	565	473	376	290	435	471	598	492	496	5569
8**	218	174	185	232	131	135	87	119	146	187	192	189	1995
9	315	245	285	352	224	159	151	156	196	288	340	270	2987
10	525	374	375	440	285	219	212	247	267	325	323	376	3968
11	305	239	252	290	181	140	112	147	179	232	281	286	2644
12**	225	169	185	223	132	103	73	119	145	194	205	195	1968
13	340	281	319	395	291	239	225	277	367	451	492	437	4114
14	322	263	345	391	276	216	230	273	320	416	424	373	3849
15	270	260	289	383	313	239	252	266	347	415	391	303	3728
16	216	167	194	298	370	262	302	338	428	383	343	208	3509
17	148	120	154	191	311	281	327	303	383	373	298	206	3095
18**	136	74	82	105	103	56	70	65	119	121	152	175	1258
19*	253	134	120	104	129	83	96	95	131	196	242	322	1905
20*	181	128	152	183	125	80	64	90	127	183	219	214	1746
21	277	248	334	469	186	114	110	139	202	332	324	246	2981
22	373	207	304	257	316	268	202	311	405	453	422	412	3930
23	314	89	76	236	211	140	155	178	230	264	258	303	2454
24*	176	127	193	241	167	85	75	95	155	228	246	206	1994
25	210	144	159	211	251	192	192	239	326	353	298	269	2844
26	160	99	108	133	150	132	145	174	215	238	249	210	2013
27*	190	150	185	208	141	82	73	108	146	210	215	195	1903
28	344	264	268	279	214	145	129	176	216	292	319	340	2986
29	217	149	199	226	169	125	116	156	224	269	277	240	2367
30	247	237	258	257	189	122	115	151	179	231	265	261	2512
31	237	151	179	191	168	122	121	126	156	181	207	215	2054
32	258	126	143	207	206	196	170	192	186	217	263	255	2419
33	478	188	286	401	371	310	238	278	316	406	475	406	4153
34	435	211	243	188	200	145	109	156	137	189	198	179	2390
35	332	310	317	310	205	157	128	157	176	217	301	315	2925
36	345	341	268	226	156	124	108	98	118	122	188	271	2360
37	419	247	256	270	225	168	152	156	170	224	350	490	3127
38	300	215	228	236	187	169	154	135	136	166	227	285	2438
39	290	252	298	288	258	217	163	161	177	226	289	296	2915
40	289	192	234	275	254	198	169	129	138	212	317	368	2775
40a	321	153	146	139	157	137	171	152	178	299	336	348	2537
41	376	260	246	266	286	191	139	151	197	350	390	359	3211
42	340	282	292	305	246	206	176	194	246	330	362	304	3283
43	306	291	315	364	295	253	196	187	210	265	305	297	3284
44	309	312	298	242	192	151	105	98	106	154	242	295	2504
45	298	299	281	216	235	212	193	142	127	113	163	229	2508
46**	171	168	168	177	164	143	107	94	103	136	157	167	1755
46a	245	271	265	245	246	221	186	218	212	229	286	276	2900
47	605	495	380	190	138	86	55	20	34	98	253	562	2916
48*	182	194	188	237	252	222	173	100	70	97	134	172	2021
49	190	199	211	288	430	385	280	109	62	86	119	178	2537
50	380	326	409	494	331	192	160	99	103	181	276	375	3326
51	162	185	204	249	221	169	137	113	129	169	196	172	2106
52	105	113	215	313	285	229	167	100	104	177	204	132	2144
53	140	145	191	232	236	233	213	161	151	135	131	141	2109
54	219	201	140	130	201	247	212	190	171	179	139	198	2227
55	310	331	250	197	184	173	144	107	128	141	222	299	2486

Table 5 continued

Type[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
56	456	389	303	241	239	199	162	114	127	153	247	375	3005
57	220	202	217	259	247	184	134	91	106	145	237	237	2279
58**	126	124	134	153	123	119	115	74	59	62	100	114	1303
59	214	160	189	251	232	249	193	120	144	154	192	195	2293
60*	193	211	201	152	139	155	128	96	53	53	71	166	1618
61	149	145	165	234	310	373	331	256	180	106	99	130	2478
62	125	130	117	255	424	626	583	375	194	145	95	122	3191
63	296	390	282	230	169	130	135	94	103	102	127	215	2273
64*	223	219	256	260	176	201	188	72	98	101	128	185	2107
65**	185	183	147	78	56	48	30	28	25	68	102	187	1137
66	366	495	291	192	132	64	35	30	35	92	181	308	2221
67	349	315	229	96	117	91	94	131	77	195	225	348	2267
68*	238	257	156	100	125	143	136	165	81	182	145	302	2030
69*	240	291	222	101	70	47	30	41	28	92	139	255	1556
70	375	425	318	201	107	56	43	58	55	125	205	345	2313
71*	289	313	197	74	37	17	9	5	4	22	98	201	1266
72*	205	230	218	172	164	115	91	23	10	71	150	212	1661
73*	243	203	178	233	227	116	43	13	7	27	67	194	1551
74*	303	299	257	224	171	144	113	69	65	96	162	258	2161
75	172	187	165	239	246	317	336	237	230	167	155	170	2621
76	273	257	288	258	173	191	139	150	116	107	154	245	2351
77	315	373	330	305	303	288	213	241	273	260	246	262	3409
78	357	321	341	253	216	203	175	156	136	148	245	328	2879
79	342	328	330	317	223	199	113	79	135	171	156	259	2652
80	226	234	212	272	315	308	236	197	230	288	194	202	2914
81	163	223	306	371	257	184	148	97	149	165	185	191	2439
82*	273	256	257	191	132	39	45	16	33	53	119	195	1609

[a]*Multiple cropping is unlikely in the area without additional water supply. **The area is not suitable for any type of agriculture unless additional water is available.



4. a) Areas of rainfall types in Indonesia (Boerema 1926). Numbers refer to the type numbers in Table 5. b) Areas of rainfall type in Indonesia, Java-Madura (Boerema 1926). Numbers refer to the type numbers in Table 5.

climatic zonation map called *Bioclimates of Southeast Asia* incorporates annual rainfall, number of dry months, and mean temperature of the coldest month for Malaysia, Thailand, Cambodia, and Vietnam (Gaussen and Legris 1966) and for Indonesia (Legris and Blasco 1974).

The criteria for a wet season calendar have been suggested (Robertson 1970). The wet season begins after 50 mm of water has accumulated in the soil according to budget calculations. It ends when soil water is less than 50 mm.

CONCLUSION

Rainfall is the most important parameter for climatic zonation in Southeast Asia not only because rice is a water-consuming crop, but also because rainfall variability is greater than that for temperature, humidity, and other climatic elements.

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II. Data acquisition and measurements

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Measurements of meteorological variables in rice-weather experiments

Z. Uchijima

With the development of crop ecology and plant meteorology, interest has gradually shifted from general to dynamic models of rice-weather relationships. In this paper, measurements of meteorological variables in rice-weather experiments were divided into two groups: simple and complex. The widely used instruments and practices for each measurement are described and discussed.

To achieve optimum growth and good yields, crops need a long growing season, air temperatures within physiological limits, sufficient solar radiation, and a large volume of water evenly distributed over the growing season. The growth and yield of crops are affected by weather fluctuations that deviate from the optimum.

Rice plants are most sensitive to temperature and water supply throughout the growing season. In temperate zones and highlands rice is frequently damaged by cool summer conditions. In tropical and subtropical regions the timing, duration, and amount of monsoon rains are critical.

Farmers and crop scientists, concerned with the influence of weather on rice production, have begun using meteorological observations to characterize the weather variation during the growing season. Special weather observation sites have gradually been established near rice experiment stations.

The dry matter production of rice plants is being studied dynamically in relation to field microclimates (Murata 1975). These studies need more accurate measurements of microclimate in the rice canopy. Agricultural meteorology has shifted from general aspects of energy balance in cultivated fields to the exchange processes of heat, radiation, water vapor, and carbon dioxide. Advanced instruments and physical principles have been introduced to clarify complicated interactions between plants and the environment. The results are used to build dynamic rice-weather models for forecasting rice growth and yield (Iwaki 1975, van Keulen 1978).

Measurements of meteorological variables in rice-weather experiments can be divided into two categories: those requiring instruments routinely used for observations in meteorological stations, and those using instruments devised especially for studying the physical processes of energy and mass transfer between plants and the aerial environment. This paper will first describe the former in simple rice-weather experiments, and then discuss the latter for complex experiments.

MEASURING METEOROLOGICAL VARIABLES IN SIMPLE RICE-WEATHER EXPERIMENTS

The main purpose of measuring meteorological variables in simple rice-weather experiments is to clarify diurnal and seasonal weather variations during the rice growing season and to relate rice yield to weather. Observatories equipped with instruments for this purpose have been established at agricultural experiment stations (Fig. 1). Such observatories must be located in fairly wide rice fields to provide representative conditions for meteorological measurement. The

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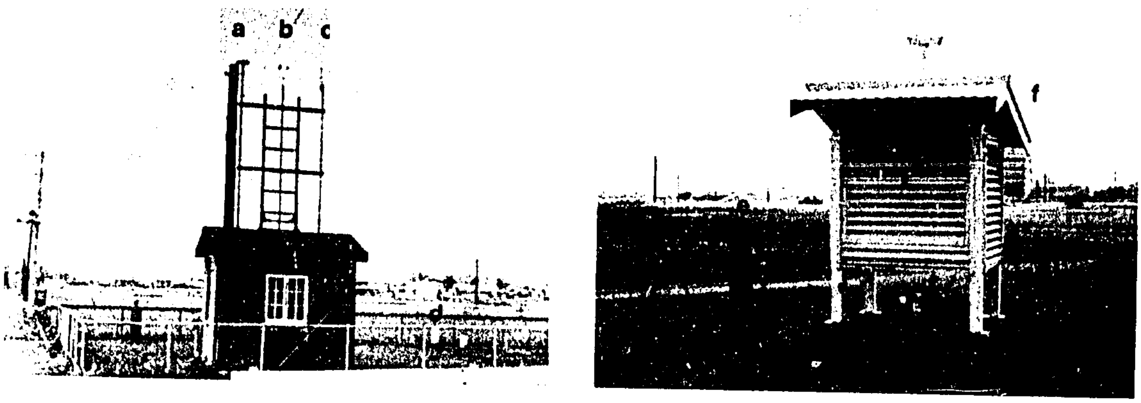


1. Meteorological observation site for rice-weather experiments (Central Agriculture Experiment Station, Konosu, Saitama Prefectures). a = Moll-Gorczynskii type solarimeter, b = rotating cup anemometer, c = wind vane, d = rain gauge, e = Jordan's sunshine duration recorder, f = meteorological shelter.

variables listed in Table 1 are usually recorded year round. Water and soil temperatures are generally measured in fields near the observatory.

Air temperature

Maximum and minimum temperatures (T_{max} and T_{min}) are read at 0900 every day directly on the mercurial and alcohol thermometers, respectively. The temperature at 0900 is nearly equal to the daily mean. The maximum thermometer is reset by whirling it so that centrifugal force drives the mercury past the constriction. The minimum thermometer is reset by turning its bulb end up so that the glass index slides down to the end of the alcohol column. The daily mean of air temperature (T_m) is calculated by:

$$T_m = \frac{T_{max} + T_{min}}{2} \qquad (1)$$

Thermographs are used to record the diurnal variation in air temperature. Weekly charts are used, but different time scales can be obtained by changing gears in the chart-cylinder drive.

Table 1. Meteorological variables measured in observatories of rice-weather experiment stations in Japan.

Meteorological variable	Instrument	Unit
Air temperature	Mercurial thermometer Thermograph	°C
Maximum temperature	Mercurial maximum thermometer	°C
Minimum temperature	Alcohol minimum thermometer	°C
Water temperature	Mercurial thermometer	°C
Soil temperature	Mercurial thermometer Bent-stem earth thermometer	°C
Air humidity	Dry- and wet-bulb psychrometer Hygrograph	%
Total solar radiation	Robitzsch pyranometer Moll-Gorczynskii type solarimeter	cal/cm^2
Sunshine duration	Jordan's sunshine recorder	h
Evaporation	small pan 20 cm in diameter	mm/day
Precipitation	Precipitation gauge Tipping bucket rain gauge	mm/day
Wind velocity	Rotating cup anemometer	m/s
Wind direction	Wind vane	

Traditional instruments are being replaced by more accurate and robust instruments such as ventilated resistance thermometers and thermistors. The output is fed to analogue or digital recorders.

Water temperature

In the higher latitudes and in highlands where thermal resources are not very abundant, water temperature strongly controls the initial growth of rice plants. The water temperature measured at 0900 is assumed to equal the daily mean. Using the water temperatures of shallow waters, Uchijima (1963) compared the daily means and obtained two methods:

$$\text{simple } \langle T_w' \rangle = (T_{w,\ max} + T_{w,\ min})/2$$
$$\text{accurate } \langle T_w \rangle = \sum_{i=1}^{24} T_{w,\ i}/24 \qquad (2)$$

where, T_w, *max* and T_w, *min* are the maximum and minimum water temperatures, and T_w, i, the water temperatures at each hour. The simple method gave water temperatures higher by several percentage points.

In regions where irrigation water comes from mountain snow, yields have been reduced significantly (Raney et al 1957, Society of Agricultural Meteorology in Japan 1962). Therefore, the temperature of irrigation water should be a meteorological factor in rice-weather experiments. Mercurial thermometers with small reservoirs (about 100 cm^3) and thermographs in which the sensitive elements are liquid-filled bulbs connected to the recording mechanisms by capillary tubes are used for measuring irrigation water temperature.

Soil temperature

Soil temperature affects the decomposition of organic material and nutrient intake by the rice plant. Although bent-stem earth thermometers are widely used for measuring soil temperature and are much cheaper than other instruments, their use in the rice field does not give a continuous record of soil temperature. Pt-resistance thermometers or thermocouples are better for recording the daily variation in soil temperature profiles.

Air humidity and dew deposition

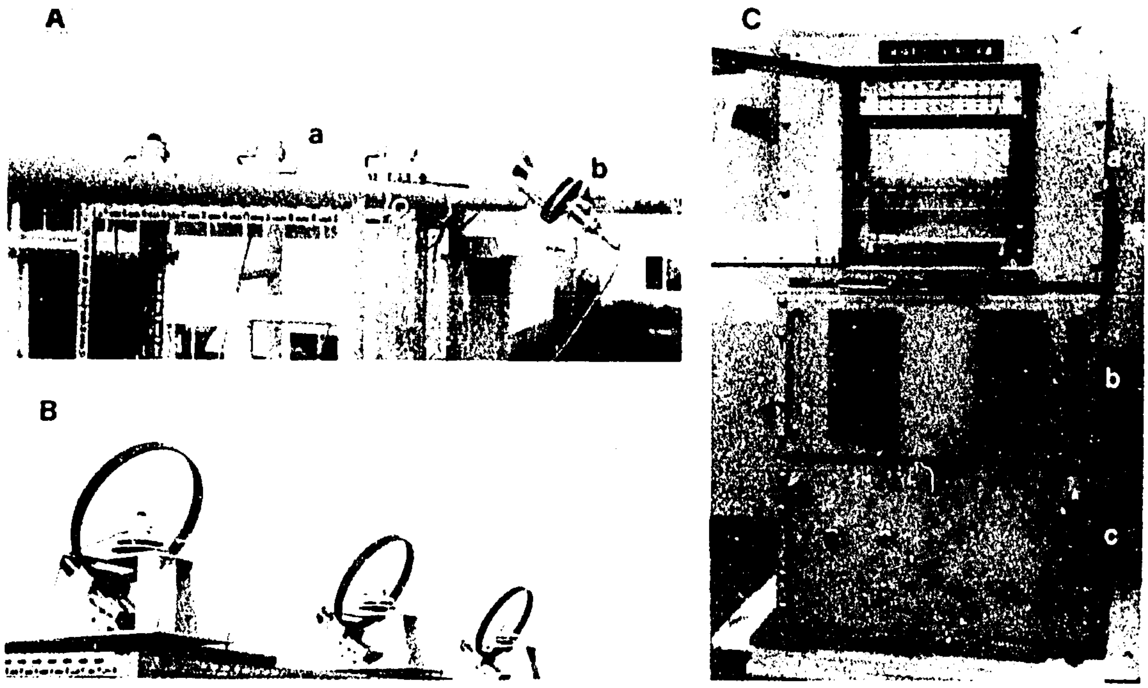
Air humidity is important to the plant pathologist because it affects the development and spread of many rice diseases. Unusually low air humidity, such as that during dry seasons and foehn, during flowering influences pollination and results in yield reductions. A wet- and dry-bulb psychrometer for measuring humidity consists of two thermometers with carefully matched scales. The wet-bulb is covered with a muslin wick. An air flow over the bulbs of at least 3 m/second provides a reliable measure of relative humidity and consequently of water vapor pressure. Motor ventilated psychrometers are used because unventilated ones are often insufficiently exposed to the air. Hygrographs with human hairs as the sensitive element are widely used to measure humidity.

The formation of dew relative to the germination of fungal spores can be characterized by three components: duration, amount, and intensity. Jennings and Monteith (1954) developed a sensitive dew-balance for recording the rate of dew deposition.

Solar radiation and sunshine duration

Solar radiation is the energy source for photosynthesis and evaporation. It is important for producing good rice yields (Matsushima 1966, Murata 1964, Kudo 1975). Bimetallic actinographs (e.g. the Robitzsch pyranometer) were first used to determine the total daily solar radiation reaching the field. Such actinographs were difficult to use and inaccurate, and have been replaced with solarimeters (e.g. the Moll-Gorczynskii and Eppley pyranometers). A typical solarimeter used in Japan is shown together with the data processing unit in Figure 2A. This system records the total incident solar radiation every 15, 30, or 60 minutes. The daily total is determined by addition.

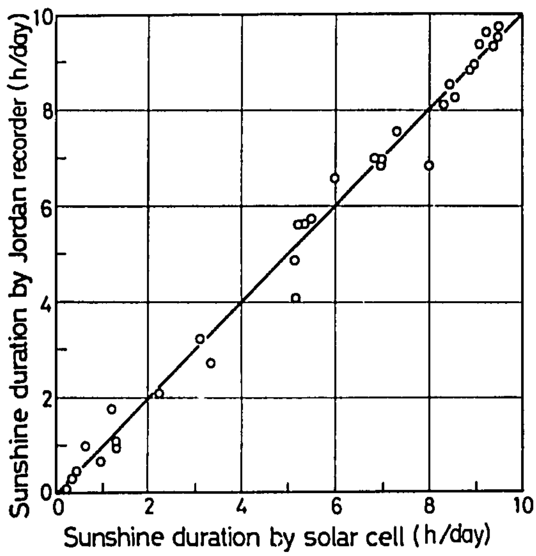
Many agricultural experiment stations are provided only with sunshine duration recorders. From records of the actual duration of sunshine, it is possible to estimate the amount of solar radiation. The Jordan recorder is the standard instrument used by the Japan Meteorological Agency (JMA). To avoid the subjective determination of sunshine duration from the path recorded by the Jordan recorder on photochemical paper, a solar-cell recorder was devised



2. A = solarimeters and element of sunshine recorder. a = solarimeters fitted with cutoff filter domes, b = solar-cell sunshine duration recorder. B = solarimeters with shading ring and cutoff filter domes. C = data logger unit. a = mV-recorder, b = analogue integrator, c = operational amplifier (Uchijima et al 1979).

(Yazaki and Kanbe 1966). The results obtained by both recorders gave good agreement (Fig. 3).

Yoshida and Shinoki (1977) statistically analyzed solar radiation and



3. Comparison of sunshine durations measured by the solar cell and the Jordan sunshine duration recorders (Yazaki and Kanbe 1966).

sunshine duration data from observatories in Japan, and obtained the following relation:

$$S_t = S_{to}\left[0.146 + 0.535\frac{n}{N} + 0.047\, G_{10} + 0.036 \sin h_o\right] \quad (3)$$

where, S_{to} is the daily total solar radiation outside the atmosphere; h_o, the monthly mean of daily maxima of the sun's elevation; and G_{10}, the snow coverage. Figure 4 compares measured and relative solar radiation with a 4.5% error using equation 3.

Evaporation

Evaporation from a 20-cm diameter pan is used as an index of the evaporation loss from rice fields (Sato 1960, Iwakiri 1965, Hanyu and Ono 1960). The relationship between small and class A pans is presented in Figure 5. The following linear relation can be obtained:

$$E_{sp} = 0.78\, E_{ap} \quad (4)$$

where, E_{sp} and E_{ap} are the daily evaporation from the small and class A pans. The JMA has adopted the class A pan as the standard instrument, but the small pan is still widely used in crop experiment stations.

Rice field evaporation consists of leaf transpiration (E_t) and evaporation from water surfaces beneath the canopy (E_w). Sato (1960) studied the water balance of rice fields using three types of evaporation tank (Fig. 6). The daily change in water level in each tank was used to separate the rice field evapotranspiration into three components: E_t, E_w, and the seepage of water into a deeper layer (E_s). Tanks 1 and 2 were iron boxes without and with bottoms, respectively, and tank 3 was a special evaporation pan. The water level in the tanks was measured daily at 0900 by hook gauges.

The following relations are used to assess each component:

$$E_s = dH_1 - dH_2,$$
$$E_t = dH_2 - dH_3, \quad (5)$$
and $$E_w = dH_3$$

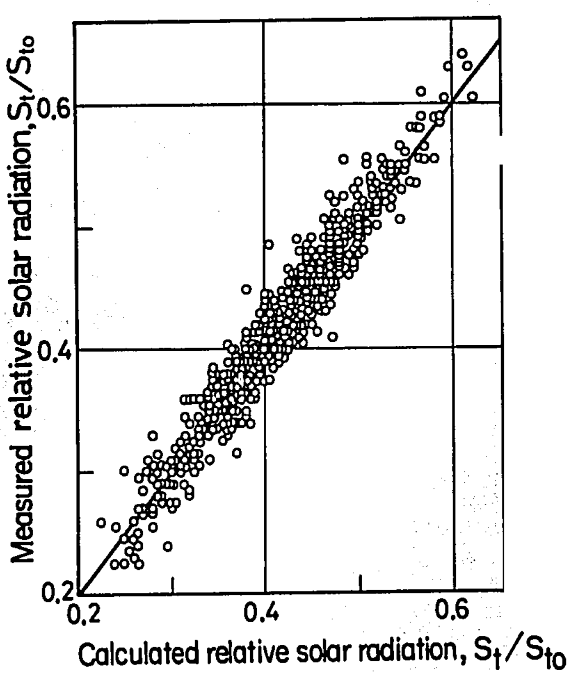
where, dH_1, dH_2, and dH_3 are the daily water level change in tanks 1, 2, and 3, respectively. The tanks are set in fairly wide rice fields to avoid the influence of local advection and of radiation enrichment due to side irradiance.

Precipitation

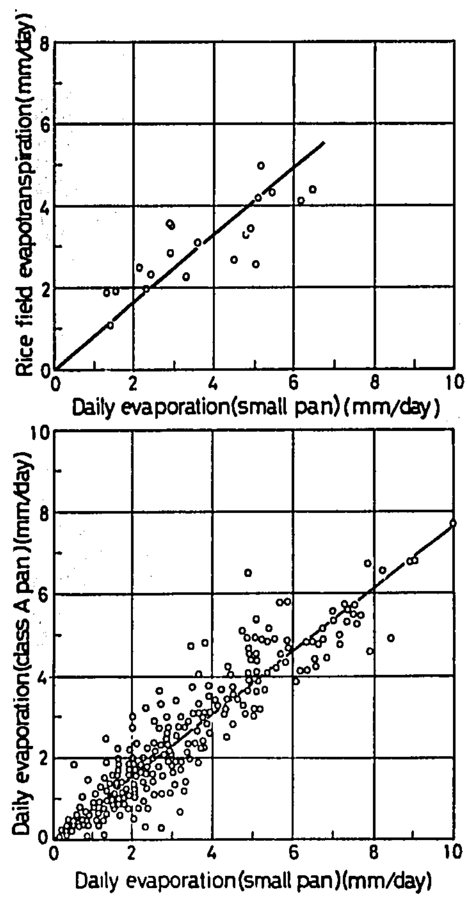
The duration, amount, and intensity of precipitation have been measured at many stations for a long time. The ordinary rain gauge with a 20-cm diameter collector gives the total amount of precipitation. The tipping-bucket rain gauge is widely used and records rain duration and the time variation of rain intensity.

Wind

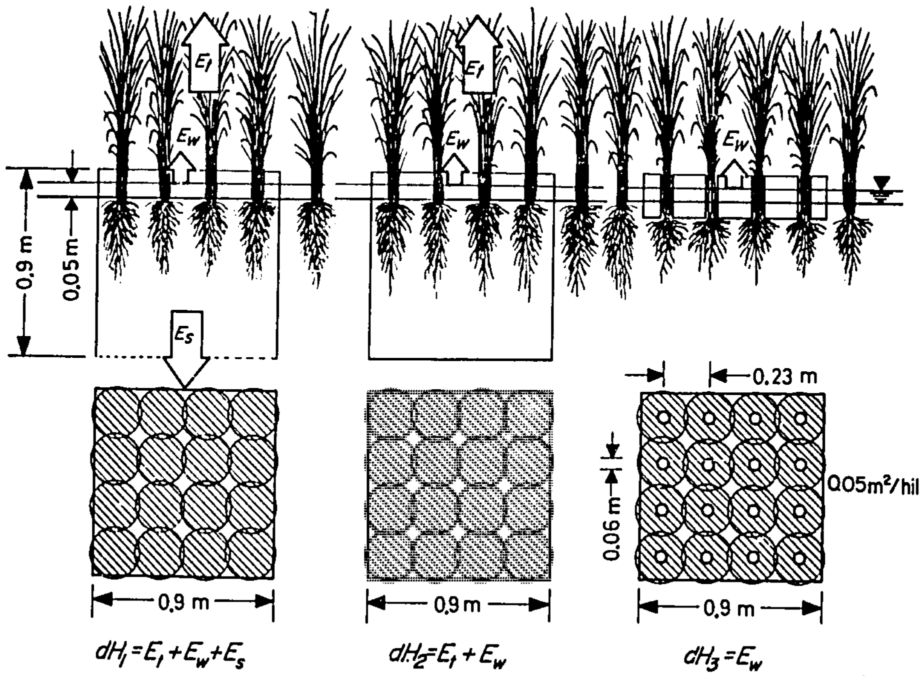
Although wind is essential in the turbulent exchange of energy and mass in the surface air layer, it is normally considered unimportant in



4. Comparison of measured relative solar radiation ($S_t S_{to}$) and relative solar radiation calculated from equation 3 (Yoshida and Shinoki 1977).



5. Comparison of daily evaporation of small pan and daily evapotranspiration in a rice field estimated by heat balance method (RGE 1967). Comparison of daily evaporation from small and class A pans.



6. Schematic representation of evaporation tanks for measuring each component of evaporation of rice fields (Sato 1960).

rice production because convection presumably develops above rice fields under calm and sunny conditions and encourages the exchange processes. Strong winds during typhoons cause lodging of rice plants and the falling and shattering of rice grains, resulting in severe yield reduction (Hitaka 1968). Wind also spreads fungal spores.

Rotating cup and propeller type anemometers mounted 8 or 10 m above the ground are used to measure wind. The mean wind velocity denotes the average for 24 hours. Assuming a logarithmic wind profile in the surface air layer, Tani (1962) showed that wind velocity immediately above the canopy is about 50% that measured at a height of 8 or 10 m.

Daily summary of variables

The meteorological variables obtained at the rice-weather experiment stations are averaged or summed every 5 days to obtain means and totals (Fig. 7). The results are generally compared with the crop calendar of rice and the seasonal variation from the norms for each variable.

MEASUREMENTS OF METEOROLOGICAL VARIABLES IN COMPLICATED RICE-WEATHER EXPERIMENTS

Special measurements of microclimate are used as input data to dynamic rice-weather models and to verify the results obtained by these models. Although little has been gained from these models so far, they have opened up a new dimension in crop ecology and plant meteorology.

Radiation measurements

Measurements of solar radiation reaching the rice field. Solar radiation is direct and diffuse. The former reaches the field surface as a direct beam (S_b) and the latter is the radiation flux (S_d), after scattering by air molecules, particles, and aerosols in the atmosphere. Solar radiation (S_t) is expressed by:

$$S_t = S_b + S_d$$

or

$$S_t = S_p \sin\beta + S_d \quad (6)$$

where, S_p is the direct solar radiation flux density at normal incidence, and β is the solar elevation. Provided S_t is invariable, the greater percentage of diffuse solar radiation is beneficial to canopy photosynthesis.

When solar radiation reaches the rice field, part is reflected and the remainder is absorbed. Solar radiation absorbed by the rice canopy is given by:

$$S_t - \rho S_t = (1 - \rho) S_t$$

and $$\rho = S_{tr} S_t^{-1} \qquad (7)$$

where, ρ is the reflectivity (albedo) and S_{tr}, the solar radiation reflected upward from the rice field. The albedo depends closely on solar elevation, leaf area index, and canopy structure.

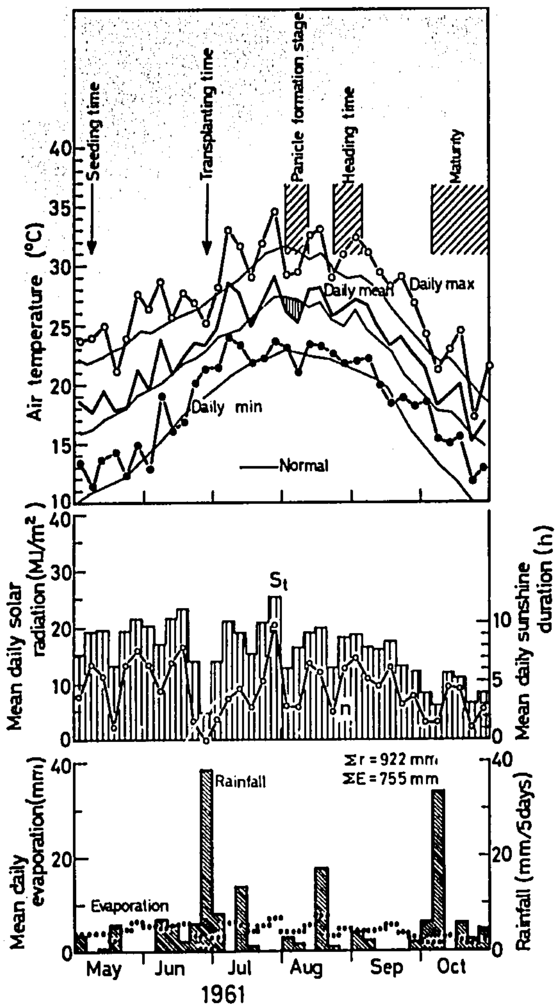
Several kinds of radiometers (e.g. solarimeter) are used to measure incoming or reflected solar radiation in rice microclimate research. The sensing element, a thermopile with blackened surfaces and protected from wind and rain by a glass dome, is uniformly sensitive to all wavelengths. The same solarimeter provided with an adjustable shading ring that prevents direct radiation from reaching the sensor can be used to measure diffuse solar radiation (Fig. 2B). A correction factor (>1.0) compensates for diffuse radiation which is excluded by the sides of the shading ring. The factor varies with the declination, δ.

Inverted solarimeters with relatively small glass domes are usually used as albedometers to measure S_{tr}. Errors due to changes in convective heat transfer patterns must be considered when a large domed solarimeter is used. The problem of proper exposure can be solved by introducing a geometric configuration factor (F_{1-2}) between the sensor and underlying surfaces (Siegel and Howell 1972):

$$F_{1-2} = r^2/(r^2 + h^2) \qquad (8)$$

This factor characterizes the radiation received from a circular rice field (radius, r and depth, h) expressed as a fraction of the total radiation. If the albedometer is set 1 m from the canopy the radii of the areas from which 90 and 96% of the total reflected radiation would come are 3 and 4.4 m. The calculation indicates that rice fields with minimum diameters of 6 or 9 m are needed to insure the proper exposure of the albedometer. This equation is also applicable to the proper exposure of a net radiometer.

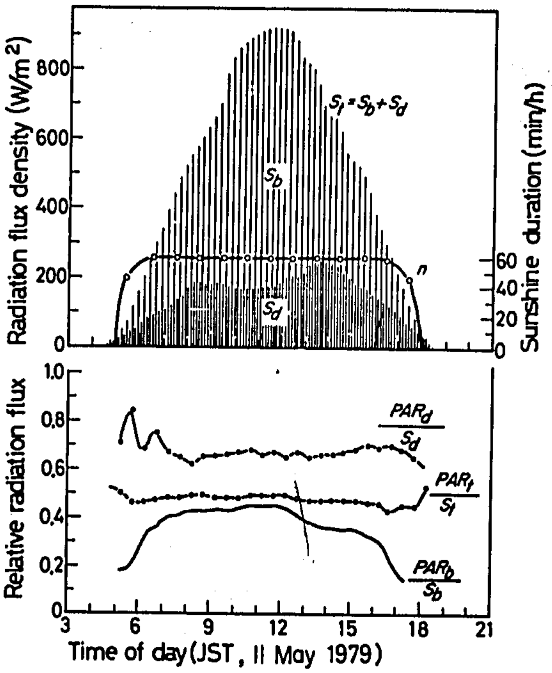
Photosynthetically active radiation (PAR; wavelength ranges



7. The seasonal variation of meteorological variables during the growing season of rice plants (Konosu, Saitama Prefectures, 1961).

from 0.38 to 0.71 μm or 0.4 to 0.7 μm) is useful in crop ecology. The percentage of PAR in the total short-wave radiation varies from 0.4 to 0.65, depending upon atmospheric turbidity, solar elevation, and cloudiness (Tooming and Gulyaev 1967, McCree 1966). Solarimeters fitted with cutoff filter domes are used to separate out PAR.

Figure 8 shows the results of solar radiation experiments at Tsukuba Agricultural Station, Japan, to measure 30-min totals of S_t, S_b, S_d, PAR_t, PAR_b PAR_d, and daily sunshine duration. The fraction of S_d in S_t is inversely proportional to the ratio of actual sunshine



8. Diurnal variation of solar radiation components (Uchijima et al 1979). S_t = flux density of total solar radiation, S_b = flux density of direct solar radiation, S_d = flux density of diffuse solar radiation, PAR = photosynthetically active radiation, n = sunshine duration per hour.

duration (n) to possible sunshine duration (N). At noon it is .25. On a clear day, the daily amount of S_d was 28% of the total solar radiation.

Measurements of solar radiation in the rice canopy. The total downward shortwave radiation $S_{tp}(L)$ at a leaf area depth of L consists of four components:

$$S_{tp}(L) = S_{bp}(L) + S_{dp}(L) + S_{bc}(L) + S_{dc}(L) \quad (9)$$

where, $S_{bp}(L)$ and $S_{dp}(L)$ are unmodified direct and diffuse radiation, respectively; and $S_{bc}(L)$ and $S_{dc}(L)$ are the complementary radiation fluxes due to scattering in the layer between the canopy top and level L. $S_{tp}(L)$ is greatly uneven in space because of the spatial variance of $S_{bp}(L)$. Therefore, a local radiation flux density average is needed to get the representative flux density within the canopy. Below crop and forest canopies, a small sensor is traversed repeatedly along a long track or a long tubular radiometer is employed to get a reliable average (Isobe 1962, Szeicz 1976, Szeicz et al 1964). Rauner (1972) proposed the following relation for evaluating the average distance necessary to get the reliable average of $S_{tp}(L)$:

$$X = 170\ \Delta \quad (10)$$

where, X is the average distance and Δ is the mean size of sunlit spots in the canopy. When Δ is around 3 cm, equation 10 gives the average distance of 5 m.

The mean flux density of $S_{bp}(L)$ and $S_{dp}(L)$ can be expressed as follows:

$$S_{bp}(L) = \tau_b(L,\beta)\cdot S_b(0),$$

and $$S_{dp}(L) = \tau_d(L)\cdot S_d(0) \quad (11)$$

where, $\tau_b(L,\beta)$ and $\tau_d(L)$ are the transmissibility of direct and diffuse solar radiation, respectively, as functions of the depth (L) and of the solar elevation (β). These two transmissibilities are given by (Ross 1975):

$$\tau_b(L,\beta) = \exp(-L\,\frac{G(\beta)}{\sin\beta}),$$

and $$\tau_d(L) = \frac{1}{\pi}\int_{2\pi}\tau_b(L,n)\ \cos\theta\ d\Omega \quad (12)$$

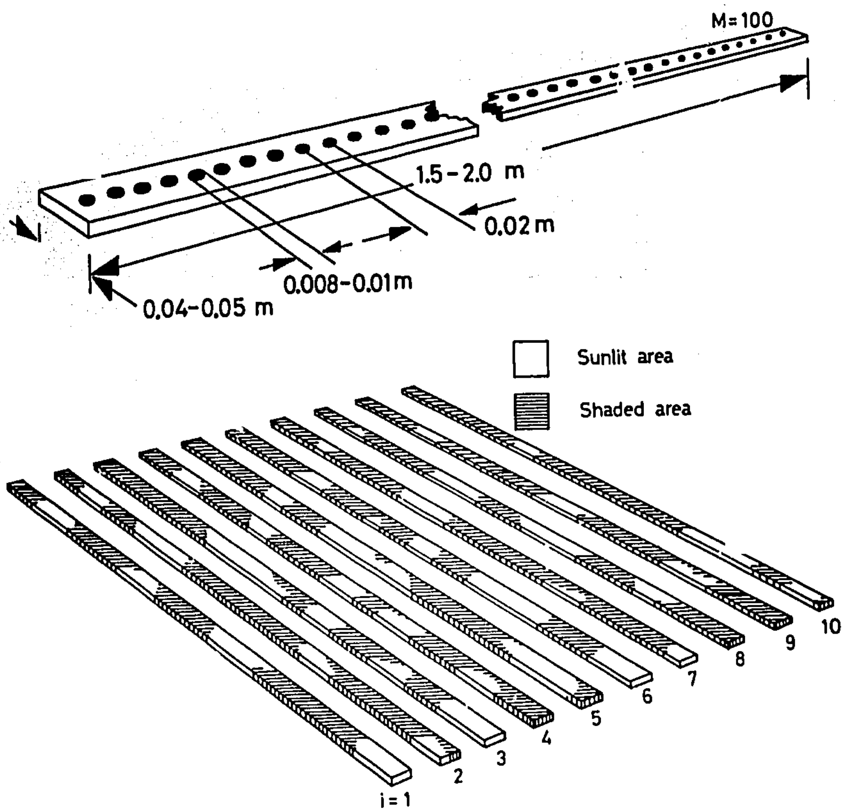
where, $G(\beta)$ is the so-called "G-function" of the plant canopy at β. The transmissibility of direct solar radiation (beam light) plays an important role in determining the radiation regime in plant canopies.

The bar measure (Fig. 9) was used to assess the fractional sunlit area in the rice canopy in relation to the solar elevation (Udagawa et al 1974, Ito, 1969). A wooden bar with 100 dark red circles on the surface is set horizontally and perpendicularly to plant rows at an arbitrary level within the canopy. The red circles in the sunlit area are counted. The bar is then reset on a new area about 20-30 cm from the previous one and circles in the sunlit area are counted. This procedure is repeated 5 or 10 times at selected levels. The fractional sunlit area at the level on which the measurements were performed is calculated from:

$$\tau_b(L,\beta) = \sum_{i=1}^{l} m_i (l\ M)^{-1} \quad (13)$$

where, l is the number of trials; m_i, the number of circles in the sunlit area at each count; and M the total number of red circles on the bar. When the rice canopy is 100 cm tall, it is preferable to make measurements at 3-4 levels in the canopy and at 4 different sun elevations.

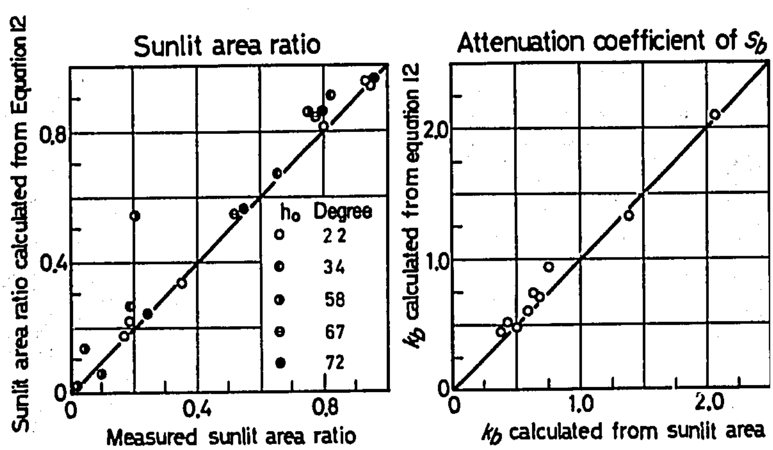
A comparison of the fractional sunlit area and extinction coefficient



9. Bar measuring sunlit area within plant canopies.

(k_b) is shown in Figure 10. The agreement between results obtained by different methods is very good, indicating that the bar measure gives a reliable measure of $S_{bp}(L)$.

Measurements of net radiation above and within the rice canopy. Net radiation is important in crop field energetics and determines thermal conditions and evaporation water loss. Net radiation,



10. Comparison of measured and calculated sunlit area ratios in the rice canopy (Udagawa et al 1974). Comparison of attenuation coefficients of direct solar radiation within the rice canopy, calculated by different methods (Udagawa et al 1974).

the algebraic sum of all the shortwave and longwave components of radiation, is given by:

$$R_n(0) = (1 - \rho)\, S_t(0) + L_d(0) - L_u(0)$$

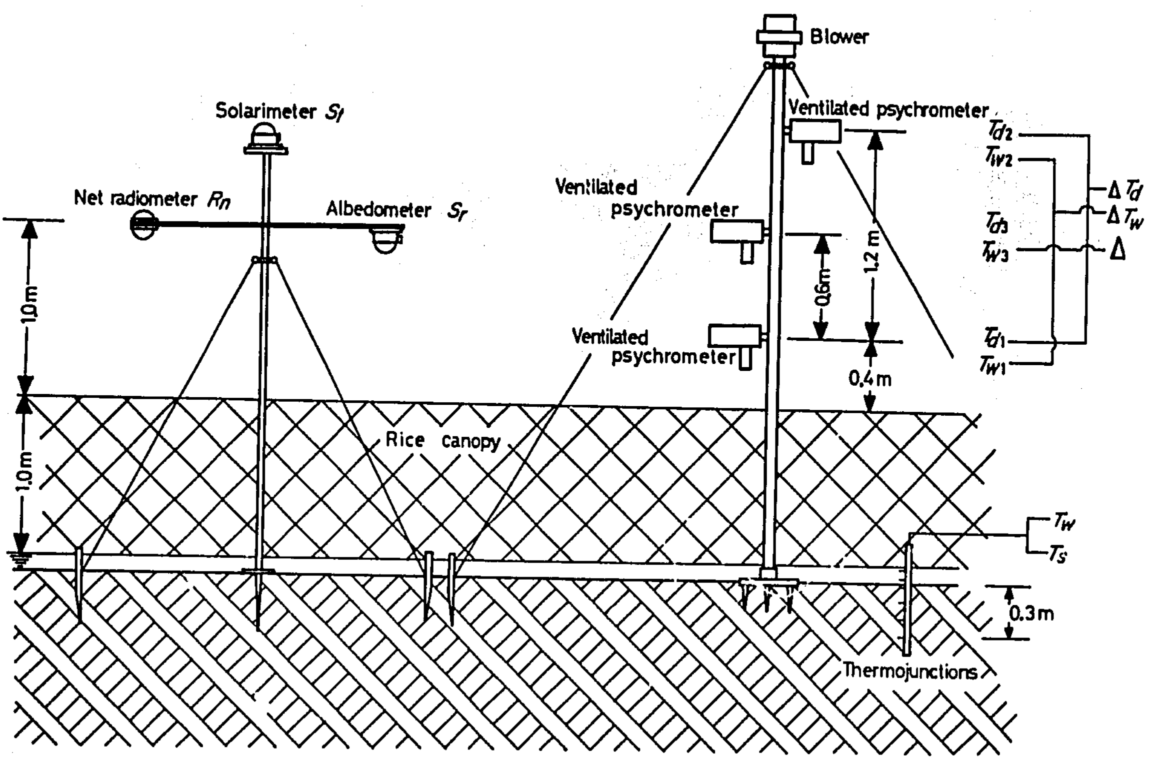
or $$R_n(0) = (1 - \rho)\, S_t(0) - F(0) \quad (14)$$

where, $R_n(0)$ is the net radiation flux density; $L_d(0)$ and $L_u(0)$, the atmospheric downward and upward long-wave radiation flux densities of the canopy top; and $F(0)(=L_d(0) - L_u(0))$, the effective longwave radiation flux density.

The ventilated net radiometer by Teledyne Geotech (USA) and the polythene shielded net radiometers by Funk (Australia) have been widely used. The ventilated net radiometers need a power supply to operate the fan, while the polythene shielded net radiometers have a disadvantage that on calm nights dew forms over polythene domes (Szeicz 1976). A light electric fan helps avoid the formation of such dew. To obtain a reliable spatial average of the net radiation flux density over a rice field, the exposure is important. Equation 8 and the method for measuring reflectivity are applicable for evaluating the proper height of the net radiometer. Such instruments are usually mounted 1 m above the canopy top (Fig. 11).

To prevent fluctuations during cloudy weather, the electric outputs of net radiometers should feed to recorders through integrators. This reduces labor and prevents loss of accuracy in determining the time totals of net radiation.

The net radiation flux density decreases very rapidly as the depth within the canopy increases but the rate diminishes because the leaves intercept direct solar radiation. Within plant communities there is much space variation in the net radiation flux density, chiefly because of the presence of plant elements. On overcast days, space variation in the net radiation beneath the canopy is not much implying that the diffuse solar radiation and effective longwave radiation are nearly invariable. The net radiation flux density ($R_n(L)$) at a level of L can be evaluated from:



11. Schematic representation of instruments for measuring heat balance components of rice fields (RGE 1967).

$$R_n(L) = \tau_b(L,\beta)\ S_{bp}(0) + R_n(L)^* \qquad (15)$$

where, $R_n(L)^*$ is the net radiation flux density measured in the shaded area at level L. Since measurements of $\tau_b(L,\beta)$ and $R_n(L)^*$ are simple and more accurate compared to the direct measurement of $R_n(L)$ by net radiometer, equation 15 should give a more reliable space average of net radiation within plant canopies.

Measurements of evapotranspiration

The measurements of evapotranspiration from rice fields has become one of the most important tasks in agricultural meteorology. Heat balance and aerodynamical methods based on the transfer of energy and mass have been applied successfully to determine the water consumption of rice fields.

Heat balance method. The latent heat flux density necessary to evaporate water from surfaces over the plant canopy (λE), can be calculated from:

$$\lambda E = \frac{R_n(0) - G(0)}{(1 + \beta)} \qquad (16)$$

where, β is the Bowen ratio; λ, the latent heat of water vaporization; and $G(0)$, the heat flux density in water and soil layers. The value of the Bowen ratio can be evaluated from measurements of air temperature and humidity at two levels above the canopy (Sargeant and Tanner 1967, Black and McNaaghton 1971, RGE 1967, Slatyer and McIlroy 1961). Assuming the equality of turbulent transfer coefficients for sensible heat and water vapor in the fully developed surface air layer, the following is obtained:

$$\beta = \frac{C_p\ P}{0.622\ \lambda}\ \frac{T_1 - T_2}{e_1 - e_2}$$

$$\text{or} \quad \beta = \frac{1}{(1 + \frac{\Delta}{\gamma})\frac{\Delta T_w}{\Delta T_d} - 1} \qquad (17)$$

where, C_p is the specific heat of air at constant pressure; p, the atmospheric pressure; T_1 and T_2, the air temperatures at levels z_1 and z_2, respectively; e_1 and e_2, the water vapor pressure at heights z_1 and z_2, respectively; γ, the psychrometric constant; ΔT_d, the dry-bulb temperature difference between levels z_1 and z_2; ΔT_w, the wet-bulb temperature difference between z_1 and z_2; and Δ, the rate of change of saturation vapor pressure with the temperature at the mean wet-bulb temperature. When β is small, as is usually observed on well-irrigated large rice areas, the heat balance method is subject to a much smaller relative error (e.g. Fritschen 1965).

Figure 11 shows the arrangement of instruments for measuring rice field evapotranspiration by the heat balance method (RGE 1967). The instruments must be set in fairly wide rice fields to ensure proper sampling of temperature profiles. Thermocouples for measuring temperature differences, ΔT_w and ΔT_d, are usually housed in ventilated dry- and wet-bulb psychrometer units so as to minimize the effects of solar radiation and to ensure more accurate measurements of temperature differences. Each ventilated psychrometer unit is connected to the blower through the setting arm and center pole to get a ventilating air speed of about 3.0 m/seconds. The air sucked through the psychrometer units, setting arm, and center pole is exhausted from the blower into the open air. When there is wind, the influence of exhausted air upon the temperature and humidity profiles in the air layer is not very large. A simple data logger is used to calculate the value of the Bowen ratio from observations of temperature differences (Sargeant and Tanner 1967, Black and McNaaghton 1971).

In our experiments, the electric outputs from each psychrometer are fed to multichannel recorders through the analogue integrators to obtain 30-minute averages of ΔT_d and ΔT_w. The daily evapotranspiration is determined by addition. The results compared with the daily evaporation of the small evaporation pan show a linear relation approximated by:

$$E_H = 0.82\ E_{sp} \qquad (18)$$

where, E_H and E_{sp} are the evapotranspiration of rice fields determined by heat balance and the small pan evaporation (5 days mean), respectively. The proportional constant of 0.82 agreed fairly well with that between the small pan evaporation and the class A pan evaporation reported by Tomitaka (1958a, b).

Aerodynamical method. In the constant flux layer over the underlying surfaces, the vertical water vapor flux (E), corresponding to evapotranspiration from the rice field, is determined by:

$$E = D_{1-2}(a_1 - a_2) \qquad (19)$$

where, D_{1-2} is the diffusion velocity and a_1 and a_2 are the absolute humidity at levels z_1 and z_2. Assuming the equality of turbulent transfer coefficients of water vapor and momentum in the fully developed turbulent layer and using the relationship between turbulent transfer coefficient and wind profile, the following relation is given:

$$D_{1-2} = \frac{\rho K^2(U_2 - U_1)}{\left[\ln \frac{Z_2-d-Z_o}{Z_1-d-Z_o}\right]^2 \psi^2} \qquad (20)$$

where, ρ is air density; K, the Karman constant 0.41; U_1 and U_2, the mean wind velocities at levels of z_1 and z_2; ψ, the parameter characterizing the influence of air stability upon the exchange process in the surface air layer (Sellers 1972); and d and z_o, the zero-plane displacement and roughness parameters.

To measure the profile of mean wind velocity above the rice canopy, four or six Casella (England) or Makino (Japan) anemometers are set on measuring masts at heights so that the interval between the adjacent anemometers becomes nearly identical to the logarithmic height scale. More than 10 minutes is generally required for representative measurements. A uniform field of a length 100 times the height of the uppermost cup anemometer is needed to ensure proper sampling. Wind profiles obtained under nearly neutral conditions are used to determine the zero plane displacement and roughness parameter of rice fields. These quantities are evaluated with the usual method using semi-logarithmic papers on which ln, z, and U are plotted on Y and X axes, respectively. Observations show that the roughness parameter is usually one order of magnitude smaller than the crop height and the zero plane displacement of the flow is generally a major fraction of the crop height h (e.g. Tani 1963, Seo and Yamaguchi 1968). Tani (1963) studied the diurnal variation in evapotranspiration of rice fields using wind and absolute humidity profiles and showed that evapotranspiration is in phase with solar radiation.

Determination of eddy diffusivity

Principle. Information about the vertical distribution of eddy diffusivity is required to determine the vertical distribution of the sources and sinks of water vapor, sensible heat, and carbon dioxide within the plant canopy. The heat balance, momentum balance, and eddy correlation methods are used to determine eddy diffusivity in rice crops (Uchijima 1962, Isobe 1965, Inoue et al 1975, Inoue and Uchijima 1979). These approaches assume that the plant community is horizontally homogeneous resulting in no systematic horizontal property gradients.

The heat balance equation for layers 0 to z combined with the turbulent transfer equation, yields the following (Uchijima 1962):

$$K = \frac{R_n(z) - G(0)}{-c_p\rho \left[\frac{dT}{dz}\Big|_z + \frac{\lambda}{c_p}\frac{dq}{dz}\Big|_z \right]} \qquad (21)$$

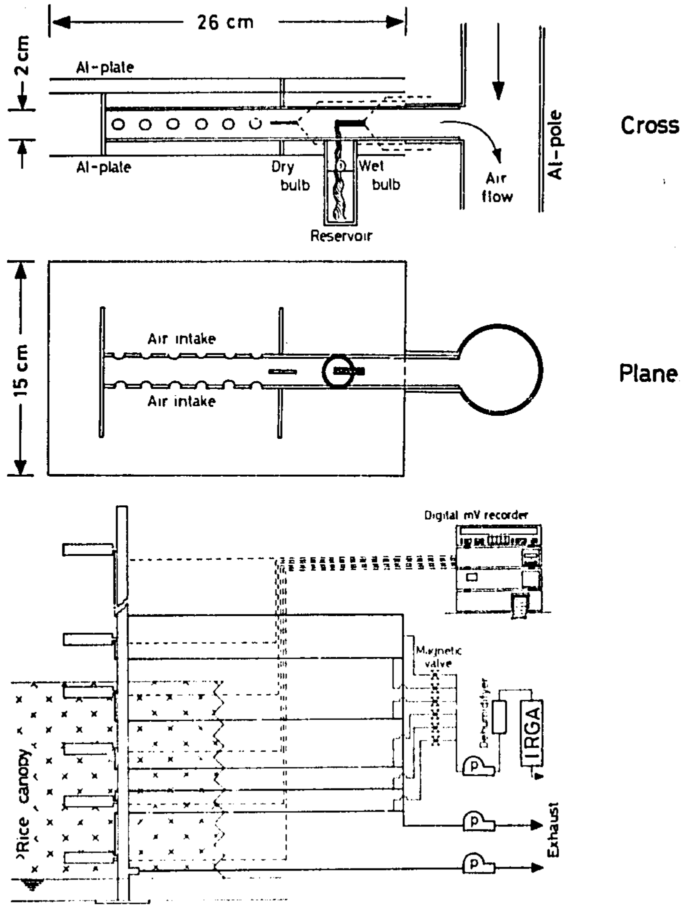
where, $R_n(z)$ is the net radiation flux density at level z; $G(0)$, the flux density of heat in water and soil layers; $dT/dz|_z$ and $dq/da|_z$, the gradients of air temperature and specific humidity at level z, respectively.

When the attenuation of momentum flux in the plant canopy is mainly due to the interaction between the air flow and plant elements, the eddy diffusivity (K) is given by:

$$K = \frac{\lambda(h) - \rho\int_z^h C_M a(z) U^2 dz}{\frac{dU}{dz}\Big|_z} \qquad (22)$$

where, $\lambda(h)$ is the momentum flux at the canopy top; C_M, the plant element drag coefficient; $a(z)$, the distribution of leaf area density; and $dU/dz|_z$, the vertical gradient of mean wind velocity at level z. Although the derivative of each quantity from inaccurate temperature, specific humidity, and mean wind velocity profiles will give inaccurate K values, the above methods can often lead to useful conclusions about the source-sink distributions in the rice canopy.

Instruments and methods. The most important point when measuring the vertical profiles of meteorological variables within the rice canopy is to minimize the disturbance caused by instrument operation. This requires small instrument. For example, the velocity of air inhaled into a ventilated psychrometer must be maintained at about 10 cm/second or less. Figure 12 shows a cross-sectional view



12. Small ventilated thermocouple psychrometer for rice canopy microclimate. Arrangement of instruments for rice canopy microclimate. IRGA = infrared gas analyzer.

of the ventilated thermocouple psychrometer and its arrangement within the rice canopy.

When the rice canopy is about 100 cm tall, four units should be in the canopy. Each unit is connected through the setting arms, the center pole, and flexible hose to the blower (Fig. 12). Aspirated air from each unit is usually exhausted into the open air leeward about 30 m from the center pole. The electric signals from each thermocouple are fed to a digital microvolt recorder with electrical compensation circuit and low-noise switching circuits. Dry- and wet-bulb temperatures are taken once each minute for 10 minutes at intervals of 30 minutes.

Part of the air blowing in each tube is sampled periodically by feeding to an infrared gas analyzer (IRGA) after passing through a dehumidifier at a rate of 1 liter/minute. The CO_2 concentration in the air is measured 3 times during the 10-minute period. The electric signals from the IRGA are fed to a one-pen recorder with a chart speed of 20 cm/hour. The CO_2 readings at each level in the canopy are averaged. The derivative of the CO_2 concentrations are multiplied by the turbulent transfer coefficient in order to determine the CO_2 vertical flux within the rice canopy:

$$F_c(z) = -K(z) \frac{d\gamma}{dz} \qquad (23)$$

where, $F_c(z)$ is the CO_2 vertical flux; γ, the CO_2 concentration in the air; and $K(z)$, the turbulent transfer coefficient to be determined by the heat balance or aerodynamical methods. The difference in the flux density between two levels within the canopy is about equal to the net photosynthetic absorption or respiration release of CO_2 in this layer:

$$F_c(z_2) - F_c(z_1) = \Delta L\ (P - R) \qquad (24)$$

where, ΔL is the partial leaf area index in the layer under consideration; and P

and R are the gross photosynthetic and respiration intensities.

The CO_2 source and sink profiles can be used to verify the results from dynamic models of canopy photosynthesis. This procedure can also determine leaf evaporation intensity (E_f) and, consequently, the stomatal resistance (r_s) that governs water vapor and CO_2 flows through the stomata:

$$r_s = \frac{2\Delta L\left(\overline{a}_s - \overline{a}_a\right)}{E(z_2) - E(z_1)} \qquad (25)$$

where, $E(z_1)$ and $E(z_2)$ are the flux density of water vapor at the bottom and top of the plant layer under consideration , respectively; a_a, the mean absolute humidity in the plant layer; $\overline{a}_s$, the mean absolute humidity in leaf stomatal cavities in the plant layer under consideration. For simplicity, $\overline{a}_s$ is approximated by:

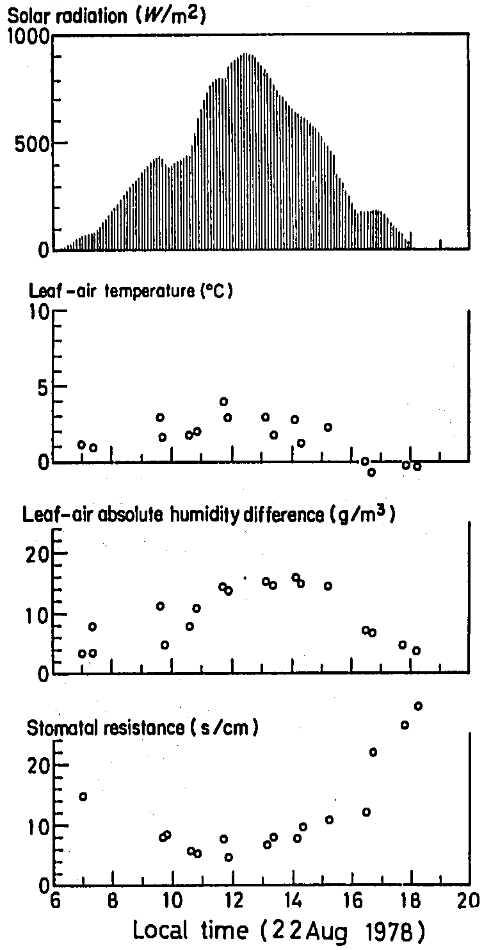
$$a_s \simeq a(T_f)$$

where, $a(T_f)$ is the water vapor pressure saturated at leaf temperature T_f. In determining stomatal resistance, leaf or canopy temperature influences the difference in absolute humidity between stomatal cavities and ambient air.

Fine-wire thermocouples, infrared thermometer, or small thermistor beads are used to directly measure leaf or canopy temperatures. Although known to give good data for the relatively large, thick leaves of maize and broad-leaved trees, the fine-wire thermocouple is difficult to insert into the narrow, thin leaves of rice plants and disturbs the leaf temperature.

The infrared thermometer is used for remote measurements of leaf, canopy, and greenhouse temperatures. Rapid spot measurement with the infrared thermometer must be repeated to get the average leaf temperature in the plant layer under consideration.

Thermistor beads are larger than fine-wire thermocouples, and are as difficult to use.



13. One example showing daytime course of stomatal resistance of rice leaf blade and related meteorological variables (Inoue et al 1979).

To develop dynamic rice-weather models, it is necessary to understand the dynamic behavior of stomata in relation to the aerial environment. The diffusion porometer by Lambda (USA) is currently used to measure stomatal resistance in the field. Figure 13 shows the daytime course of rice leaf stomatal resistance compared to relative meteorological variables.

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Measurement of evapotranspiration in rice

V. S. Tomar and J. C. O'Toole

A brief review of techniques used to measure or estimate evapotranspiration (ET) from wetland rice indicated that the high correlation between expense and accuracy made few methods broadly acceptable. In this paper, the design, construction, and field testing of a simple, sensitive, and accurate microlysimeter for wetland rice fields are described. Seasonal and diurnal variations in transpiration and evapotranspiration in relation to climatic variables are discussed. Daily variations indicate that the dry season evapotranspiration rate is about twice that of the wet season. High solar radiation, vapor pressure deficit, and wind speed are responsible. Hourly measurements of evapotranspiration illustrated the close diurnal relationship between evapotranspiration and vapor pressure deficit. When data from both wet and dry seasons were combined, however, there was a good curvilinear relationship between the hourly values of transpiration and evapotranspiration and the vapor pressure deficit.

Evapotranspiration (ET) is the process of converting liquid water from soil, water surfaces, and plant tissues to vapor and mixing it with the atmosphere. This process is a primary component of the energy exchange function that determines the production potential of crop species and the distribution of natural vegetation. Accurate ET measurements will aid in designing, engineering, and managing irrigation facilities; developing sound, agronomic, irrigation practices; determining the water balance of rainfed rice and estimating supplementary irrigation or water conservation goals to meet the crop's water requirement; evaluating the suitability of cropping patterns based on estimates of the water balance for a particular area; and classifying rice environments where genetic and agronomic technology may be transferable.

Estimating actual and potential ET has been the subject of extensive research. Micrometeorological, empirical, and water balance or hydrologic methods have been employed. The methods differ in short- and long-term accuracy,. convenience, and cost. Tanner (1967) reported that the choice of method depends on its application. For example, annual or monthly ET estimates with 15 to 20% error can be used in planning regional irrigation and water resource developments. On the other hand, detailed research on water transfer in the soil-plant-atmosphere continuum and on plant response to water stress requires measurements over periods as short as a few minutes or as long as 1 or 2 days with errors as low as 5%. This paper briefly discusses the various techniques employed to measure ET from rice fields, and the use of a microlysimeter to measure ET from wetland rice fields.

METHODS FOR MEASURING EVAPOTRANSPIRATION

Micrometeorological methods

Micrometeorological measurements of water vapor flux densities in the boundary layer of the atmosphere are used to infer ET. The methods allow ET measurements over short time periods, provide flux measurements in addition to ET, and provide other environmental information relevant to plant studies. Although quite sensitive, these methods require complex instrumentation, which may offset the advantages.

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The Research Group of Evapotranspiration (RGE, 1967) in Japan reported accurate ET estimates from paddy fields by heat balance and combination methods. The values obtained by both methods were lower than the total evaporation measured by a 20-cm-diameter evaporimeter. RGE did not report measuring ET directly. However, results obtained with the combined methods by Evans (1971) at Griffith, New South Wales, Australia, were inconsistent when compared with lysimeter values from a wetland rice crop. The major reason was probably the high wind dependence of crop roughness. In a review of the physics of ET, Sellers (1964) concluded that dependency on net radiation as the parameter for estimating ET in arid regions is not warranted.

Empirical methods

Empirical formulas relating climatological measurements and ET are best for estimating potential ET for large areas. Doorenbos and Pruitt (1977) discussed several methods for estimating potential ET from rice fields. Empirical methods need calibration against measurements from specific crops in a given region. Many researchers have tried to calibrate the empirical methods against actual field ET measurements from wetland rice (Evans 1971, Ghildyal and Tomar 1976, Lenka 1978, Surya Rao et al 1975). However, the methods are limited because they do not account for advective energy.

Pan evaporation to which various crop coefficients have been applied has been used to estimate ET. Van Woudt (1966) showed that under arid and semi-arid conditions, the pan evaporimeter has the advantage of integrating to some extent the effects of advected heat. This is probably why the pan evaporimeter was advocated for such conditions (Stanhill 1965). Various ratios of ET to pan evaporation from rice fields have been reported across varying geographic regions and seasons. Tomar and O'Toole (1979) reviewed the available literature and concluded that a ratio of 1.2 is reasonable for the season. The ratio varies over the growth stages. These facts seem peculiar to studies on rice and differ from results from crops adapted to drylands.

Water balance methods

The water balance methods involve catchment hydrology, soil moisture depletion sampling, and lysimeters. Lysimetry is the only hydrologic technique that gives complete information for all the components of the water balance equation. For dryland crops, weighing lysimeters are necessary for daily or hourly measurements. In wetland rice culture, however, the change in submerged water level in tanks with bottoms is measured as ET. Tank lysimeters of different shapes and sizes have been used to gather ET information from wetland rice fields. They also serve as an independent check on the suitability of micrometeorological methods and in the calibration of empirical formulas for estimating potential ET (Brown et al 1978, Evans 1971, Ghildyal and Tomar 1976, Lenka 1978, Kung et al 1965, Pande and Mitra 1971, Patel et al 1979, Sugimoto 1971, Vamadevan 1971, van Woudt (1966). Here we discuss a simple microlysimeter that can be used with great precision in wetland conditions.

MICROLYSIMETER

Design and construction

In wetland rice culture, the soil surface is submerged 5 to 10 cm during the crop's entire growth period (except for the last 2 weeks). The microlysimeter was therefore designed to measure ET while maintaining a constant submergence level matching that of the surrounding field. ET is calculated by measuring the decrease in the water column height in the reservoir (Fig. 1). The unit consists of two principal parts: the polyvinyl-chloride (PVC) cylinder with a closed bottom, and the Mariotte system to maintain a constant water level in the PVC cylinder and to serve as a reservoir-manometer. At 5 cm below the upper rim, the PVC cylinder (60 cm long, 20 cm internal diameter) is connected to the Mariotte system by flexible tubing. The Mariotte system consists of a reservoir-manometer of clear glass tubing (100 cm long, 2 to 5 cm internal diameter) and a bubble tube (100 cm long, 0.7 cm outer diameter). The upper end of the bubble tube is open to the atmosphere and the lower end is adjusted to maintain the desired water level inside the PVC cylinder.

Calibration

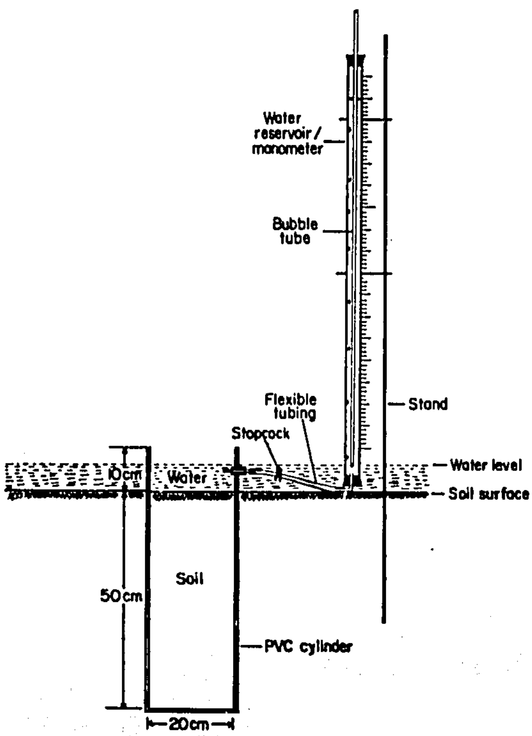
The volume of water delivered from the reservoir-manometer into the PVC cylinder to maintain the constant water level is considered as evapotranspiration for that time interval:

$$ET = \frac{(\pi r_o^2 - \pi r_i^2)}{A} \frac{\Delta h}{\Delta t}$$

where, ET is evapotranspiration (cm^3/cm^2 per h), r_o is the inner radius of the outer tube (cm), r_i is the outer radius of the inner tube (cm), A is the effective surface area (cm^2) of each hill, Δh is the change in water column height in the reservoir (cm) in Δt time (h). Δt is chosen according to the researcher's needs. The effective area of the cylinder was 314 cm^2, equal to the inner cross sectional area of the cylinder till when the leaf area index (LAI) is one. Thereafter, when the canopy covered more ground surface (LAI > 1), the effective area was 400 cm^2, equivalent to an area represented by each hill in a 20- x 20-cm planting pattern.

Field installation

After field preparation, 60-cm-long PVC cylinders were buried upright in the soil so that 10 cm remained above ground (Fig. 1). Each cylinder was refilled with the same soil to the field level. One hill of rice was transplanted into each cylinder to match the planting pattern in the surrounding field. The Mariotte system was set in place beside each PVC cylinder and the rubber tube connected. The microlysimeters were reached by a walkway of planks. After the necessary agronomic practices, the plants were grown under submerged (5 to 6 cm) soil conditions. The reservoir-manometer is filled with water, and the height of the water column is measured with a meterstick. Readings are taken at desired time intervals.



1. Cross section of a microlysimeter installed in the rice paddy.

RESULTS AND DISCUSSION

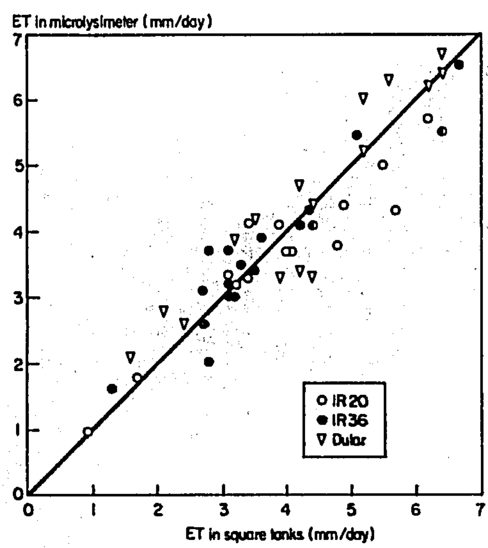
Field testing

To verify the reliability and accuracy of the results, large square tanks (40 x 40 cm) with a capacity of 4 hills were installed along with the microlysimeters in the 1978 wet season. Data for three rice cultivars -- IR20, IR36, and Dular -- were collected from 15 days after transplanting until flowering.

There was good agreement between the results obtained with microlysimeters and with square tanks (Fig. 2). The distribution of data points along the 1:1 line clearly indicates that single hill microlysimeters can be used to measure ET under field conditions.

Seasonal variations in ET

Water lost as transpiration (T) or ET is generally higher in the dry season than in the wet because of high atmos-



2. Comparison of evapotranspiration (ET) measured with microlysimeters and square tanks.

Table 1. Daily transpiration (T) and evapotranspiration (ET) of IR36 and pan evaporation with climatic conditions, 1978 and 1979 dry seasons.

Period[a]		T (mm)	ET (mm)	Class A pan evaporation (mm)	Solar radiation (cal/cm^2 per day)	Total wind run (km/day)	Mean vapor pressure deficit (mb) 0800-1800 h
1978	11 Apr	9.07 ± 0.44	-	7.90	639	110.2	17.4
	12 Apr	9.50 ± 0.57	-	8.58	665	126.8	15.8
	13 Apr	-	11.02 ± 0.62	8.80	663	102.8	17.8
1979	26 Mar	-	8.25 ± 0.42	6.60	615	142.1	21.3
	20 Apr	-	10.62 ± 0.57	5.90	635	54.5	13.9

[a]Leaf area index (m^2/m^2) was 6.8 during 11-13 Apr 1978, 1.8 on 26 Mar, and 4.8 on 20 Apr 1979.

Table 2. Daily transpiration and evapotranspiration of IR36, pan evaporation and solar radiation, 1978 wet season.

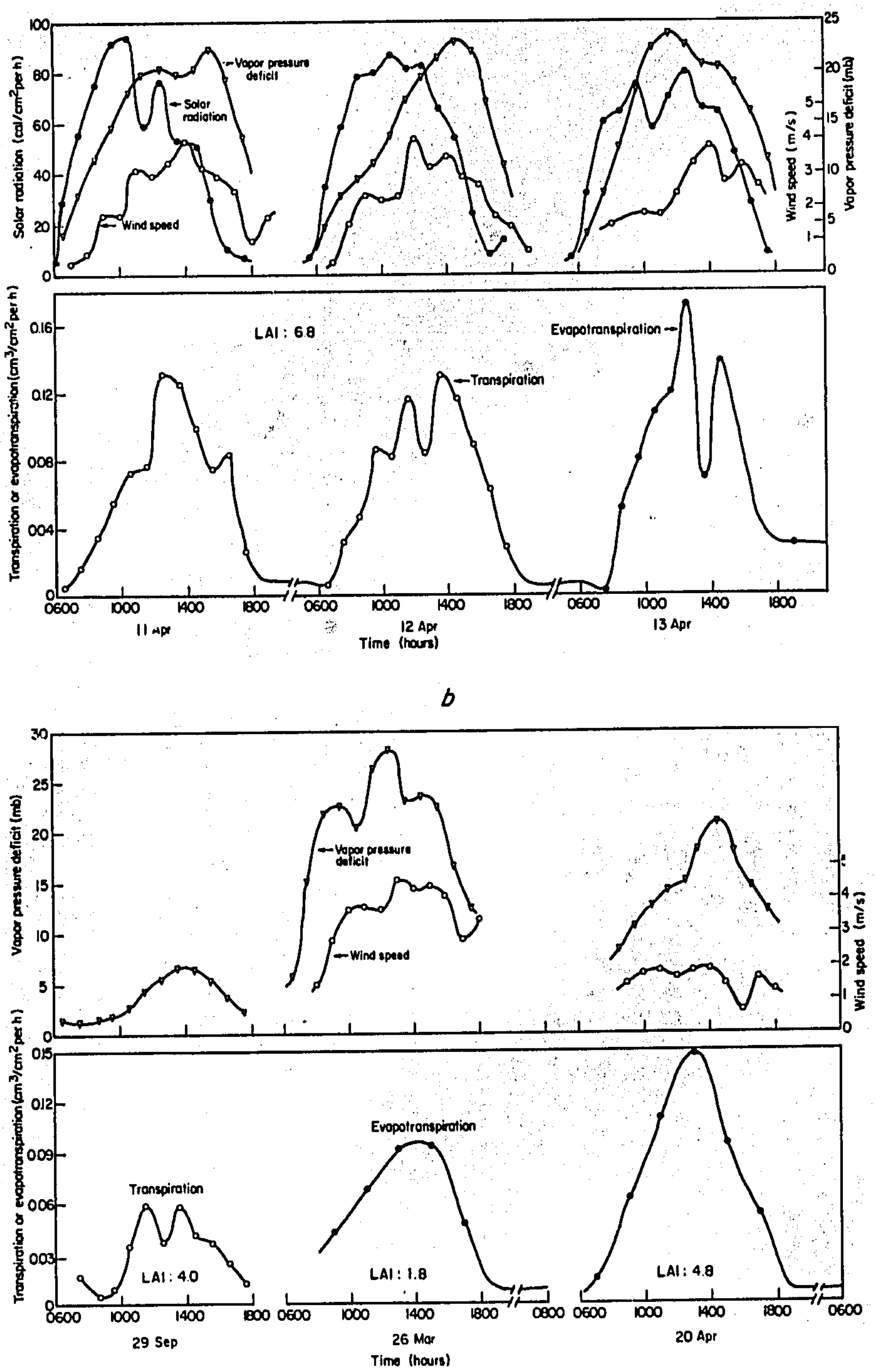
Period[a]	Transpiration (mm)	Evapotranspiration (mm)	Class A pan evaporation (mm)	Solar radiation (cal/cm^2 per day)
25 Sep	-	4.91 ± 0.67	4.8	571
29 Sep	3.3 ± 0.27	-	3.2	392
4 Oct	-	5.50 ± 0.37	3.8	441
5 Oct	-	7.23 ± 0.60	5.3	563
27 Nov	-	5.8 ± 0.65	4.2	422
28 Nov	-	5.65 ± 0.36	4.8	451
18 Dec	-	3.95 ± 0.34	3.2	384
19 Dec	-	4.31 ± 0.62	4.2	476
27 Dec	-	3.90 ± 0.30	3.5	365
28 Dec	-	3.61 ± 0.23	3.5	372

[a]Leaf area index (m^2/m^2) was > 3.5 during 25 Sep-5 Oct, < 1 on 27-28 Nov, and > 4.5 during 18-28 Dec.

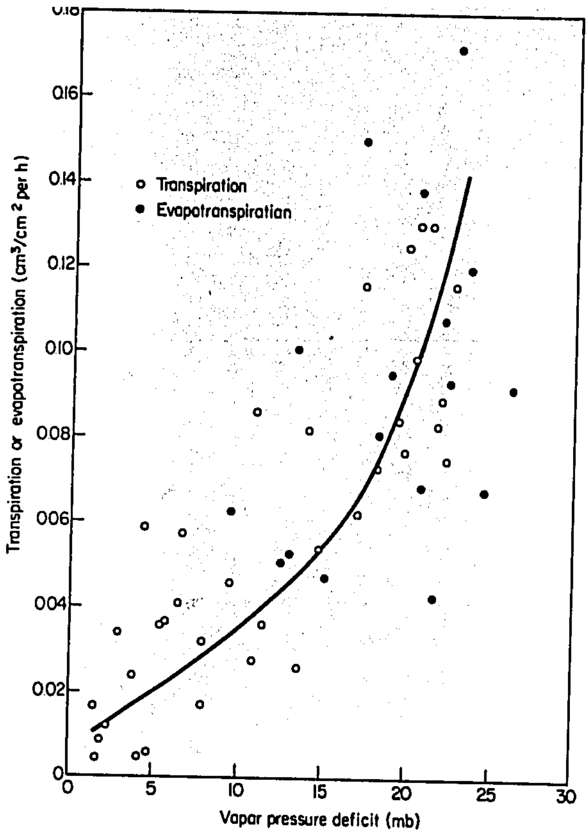
pheric evaporative demand. Daily T and ET measurements for IR36 during some selected clear days in the 1978 and 1979 dry seasons are reported in Table 1. To measure T, the cylinders were covered with perspex sheets to stop evaporation from the water surface. In both dry seasons, the high total solar radiation (650 cal/cm^2 per day), total wind run (>100 km/day), open pan evaporation (8 mm/day), and the vapor pressure deficit during the day (17 mb) illustrate the high evaporative demand that characterizes the season of highest productivity at this location. The T and ET rate from wetland rice fields during this dry period, when the LAI was more than 4, was 10 mm/day. High advection in the dry season causes a high water loss rate and open pan evaporation will considerably underestimate the actual water loss rates from irrigated rice fields. T and ET losses for a few selected days in the 1978 wet season are given in Table 2. Average solar radiation (440 cal/cm^2 per day) and pan evaporation (4 mm/day) were lower in the wet season than in the dry (Table 1). ET losses were only about half (5 mm/day[1]) that of the dry season. Daily ET was either equal to or more than open pan evaporation.

Diurnal variations in ET in relation to climatic conditions

Hourly measurements of T, ET, solar radiation, vapor pressure deficit, and wind speed during the 1978 dry season are illustrated in Figure 3a. The hourly water loss rate was maximum from 1200 to 1400. The diurnal pattern appears to relate well with the integrated effect of all climatic variables. Solar radiation was higher during the forenoon hours,



3. a) Diurnal variations in transpiration and evapotranspiration of IR36 with solar radiation, vapor pressure deficit and wind speed on 3 clear days, 1978 dry season. b) Diurnal variations in transpiration and evapotranspiration of IR36 with vapor pressure deficit and wind speed on (clear days) 29 September, 1978 wet season, and 26 March and 20 April, 1979 dry season. LAI = leaf area index.



4. Relationship between hourly transpiration (LAI > 4) and evapotranspiration of IR36 with vapor pressure deficit. Data presented are from Figures 3a and 3b.

whereas vapor pressure deficit was high during the noon and afternoon hours. Among the climatic variables, the vapor pressure deficit appears to show the predominant effect on hourly water loss rates.

Variations in T and ET along with vapor pressure deficit and wind speed for selected days in 1978 wet and 1979 dry seasons are shown in Figure 3b. The transpiration rate from a rice canopy with LAI 4, considered roughly equivalent to ET, was low; on 29 September, even during peak periods of water loss, it was only 0.6 mm/hour. In the dry season, ET was high during the early growth stage (26 Mar; LAI = 1.8) and during flowering (20 Apr; LAI = 4.8). The diurnal trend correlates well with the vapor pressure deficit for these days (Fig. 3a).

Because vapor pressure deficits greatly affect the diurnal trend in water loss rate, hourly T and ET rates for both seasons were plotted against the respective vapor pressure deficit values. Data points were much diffused because other climatic parameters besides vapor pressure deficit affected water loss (Fig. 4). But the water loss rate increased almost linearly up to 0.8 mm/hour with the vapor pressure deficit. Thereafter, water loss increased almost exponentially at higher vapor pressure deficit values. In general, water loss rate increased curvilinearly with vapor pressure deficit.

In conclusion, these observations illustrate the applicability of the simple and inexpensive microlysimeter for direct measurement of ET of irrigated rice. The monitoring of other climatic and crop variables aids in our understanding of the relationship between crop growth (increasing LAI) and the principal weather factors (solar radiation, wind speed, and vapor pressure deficit) acting on an irrigated rice crop canopy to effect the role of water flux to the atmosphere.

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Minimum data requirements in rice experiments

J. F. Angus

A minimum data system proposes that a standard set of crop and environment observations should be collected from regional field experiments, such as variety, fertilizer, or time of planting experiments. When data from a series of field experiments are analyzed together, the major environmental factors and treatment effects can be understood and ultimately quantified and managed.

The parameters to be measured should be chosen by field workers experienced in a region and should represent factors responsible for most of the yield variation from site to site and from year to year. An example of a proposed minimum data set for rainfed lowland rice is presented. The likely organizational, data-handling, and analytical problems of the system are discussed.

In a field experiment, the yield is determined by the interaction of controlled factors--the experimental treatments--and by uncontrolled factors --the environmental variation. Agronomists are traditionally concerned with the controllable variation while recognizing that uncontrolled factors affect their results. Their approach to the uncontrolled variation has been to exhaustively repeat an experiment over seasons and sites so that robust experimental treatments could be identified and recommended.

Another school of crop scientists is concerned with the crop-environment interaction, where environmental variation is assumed to be largely due to weather influence. The pioneers in this field established correlations and simple models between crop performance and weather parameters (e.g. Abbe 1905). More recent methods are based on systems analysis and simulation techniques (e.g. van Keulen 1976). Generally, workers have used data either from well-controlled experiments supplied with optimal inputs, or from regional farm yields which have constant management conditions. Systems analysis can now potentially account for the variation due to weather and for much of the variation due to experimental treatments.

Rice is grown in a variety of cultural systems (e.g. dryland, irrigated, rainfed wetland, deep water) and the data required to account for the yield variation differs for each system. A discussion of the requirements for every system is beyond the scope of a single paper. This paper is concerned only with rainfed wetland rice, a major cultural type in South and Southeast Asia (Barker and Herdt 1978).

A minimum data set for rice experiments is proposed to provide integrated crop-environment information from which models that account for both environmental and treatment effects can be developed.

BACKGROUND

Proposals for standardized data collection programs for field experiments have been made by Collis-George (1972), Frere (1972), and by Nix and associates (Nix 1973, Angus et al 1974). A FAO consultation, organized by Nix in 1977, recommended that minimum data systems be adopted in national research programs.

The principle of collecting standardized data is implicit in several national and international field research programs, such as the Australian National Soil Fertility Project, the Asian Cropping Systems Program, and the World Meteorological Organization Wheat Crop Ecology Project.

A minimum data set should be tailored for the specific needs of a region, and the required observations should be decided by a consensus of experienced scientists who can identify the factors most important in causing crop yield variation.

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Agrometeorological data alone are insufficient for a description of the environment. Soil, biotic, genetic, and management factors affect yield even in the most carefully controlled field experiments, but it would be impossible to measure all or indeed most of these factors even if appropriate analytical methods were available. The important requirement is that the factors determining most of the yield variation should be measured.

Ideally, factors to be measured should be determined from surveys or prior experimental data. In practice, the intuitive opinions of local agronomists may be the only source of information for some regions. The mental model of a skilled and experienced observer may very well be superior to data based only on a few years' observations.

If experiments are to be superimposed on farmers' fields, then it is necessary to record some socioeconomic data about the farmer. Variations in productivity from field to field may depend as much on the management skills of the farmer as on imposed treatments or environmental factors. Because the inclusion of social factors adds a whole new dimension to the tasks of data collection and analysis, we shall assume that an experimental program is carried out with a more uniform and higher level of management control than could be expected from a random selection of farmers.

Observation sites should be located over a wide geographical range of the cultural system. Sites that have extreme conditions should be included to define environmental limits. The choice of a site should be based on an expectation of all data being collected. If key data are unavailable then no other data from the site can be used.

A minimum data system is most useful for large interactions between environment and yield response to management inputs. For example, in dry or cloudy seasons the yield response of rainfed rice to applied nitrogen would be less than in wet or sunny seasons. A minimum data system could not be recommended when important treatment responses are relatively consistent between years. For example, for a given soil a consistent response to applied micronutrients would be expected in different seasons.

DATA COLLECTION

A proposal for the minimum data requirements for rainfed wetland rice is presented in Table 1. Minimum implies the least additional time and cost over the input normal in a regional field experiment. This proposal is based on detailed measurements at the times of planting and harvest, a visit at the time of anthesis, and as many other visits as possible.

Crop-related data

The total biomass and the grain yield should be estimated at the maturity harvest. The measurement of total biomass is needed in calculating nutrient uptake, which can help identify deficiencies and the extent of fertilizer losses. Observations of phasic development are important in identifying the onset of stress at critical periods in crop development. The harvest index (ratio of grain to total biomass) can indicate the severity of post-anthesis stress.

Weather requirements

Special attention should be given to temperature, evaporation, and humidity measurements in and near flooded fields. In a recent comparison of weather measured in an irrigated field at IRRI and at the nearby (1 km) upland station at the University of the Philippines at Los Baños (Angus and Manalo, in press), we found considerable differences which could be explained by the higher atmospheric humidity and the diurnal thermal buffering of the flooded environment.

The labor and high cost of recording weather data make it easier to bring experiments to weather stations than vice versa. The acceptable distance and difference in terrain between a weather station and an experimental site vary with individual weather elements. The guidelines given below are necessarily subjective.

1. *Rainfall.* The most variable element in both time and space is rainfall. The gauge in water use or irrigation efficiency experiments should be within 1 km of the experimental site. If the area has a steep rainfall gradient or is subject to irregular storm activity, the gauge should be within the plots.

2. *Evaporation.* The class A pan has become the unofficial standard for measuring evaporation in many crop studies. It is cheap, easy to make and use, and the unscreened pan is suitable for studies of rice evapotranspiration. Because evaporation is much less variable

Table 1. An example of minimum data requirements for accounting for the variation in yield of rainfed wetland rice.

	Minimum data requirements			
	Environmental	Crop-related	Biotic	Management
Daily	Water depth (if flooded) Water table depth (if not flooded) Rainfall Class A pan evaporation Solar radiation Screen temperature (max, min, wet, dry)			
Once per season	Starting value of soil (N (P (K	Grain yield Total biomass Uptake of N, P, K at maturity	Weed wt and no. (at anthesis?)	Field history (5 years?) Experimental treatments, cultivars & inputs
Inspect for and report		Dates of (planting or (transplanting (anthesis (maturity		
Inspect for and report		Lodging) Poor stand) date and Natural disasters) rating	Pest and diseases not controlled by pesticides etc.) date and rating of damage	Major operations on soil and crop
Once ever	Soil (pH & conductivity (bulk density (water content at saturation and at the "lower limit" for rice			

over distance than rainfall, the experiment should be situated no farther than about 10 km from the pan, provided there are no differences in exposure due to towns, lakes, trees, hills, or irrigation areas.

3. *Solar radiation and sunshine duration*. Solar radiation is an important yield determinant for high-input flooded rice (Moomaw et al 1967). Radiation measurements are not easy to take because the most sensitive and accurate instrument, the pyranometer, rapidly deteriorates and requires frequent calibration in tropical rice-growing areas. Unfortunately there are no primary calibration sources in the region.

The Gunn-Bellani radiometer deserves general reconsideration for the low-latitude isothermal regions. Inexpensive and self-contained, it can be used successfully for long periods by relatively unskilled observers (M.W. Dagg, personal communication 1979).

A sunshine duration recorder can be used to estimate daily radiation totals using an empirical relationship established for a region. Data for at least 5 years are necessary to establish this relationship. If they are not available, the double expense of a sunshine recorder and a standard radiometer must be incurred.

An experiment need not be situated in the immediate vicinity of a adiometer. However, instruments should not be in unrepresentative sites such as cities with air pollution or on cloudy coastlines.

4. *Temperature*. Temperature seldom has a large direct effect on rice productivity in the lowland tropics. Outside the humid lowland tropics low temperature defines the limits for rice cultivation, and high temperature at various development stages can seriously affect yield (Satake and Yoshida 1978). Accurate temperature records are important for humidity calculations and in interpreting biological processes, such as insect development and rates of soil nitrogen transformations.

Daily maximum, minimum, and wet and dry bulb temperatures should be recorded with mercury- or alcohol-in-glass thermometers kept preferably in a standard meteorological screen or, at least, in a free-standing shelter which provides air circulation. The wet and dry bulb temperatures should be measured at the local standard recording time. The acceptable distance between temperature-screen and experimental site is the same as for the evaporimeter and solarimeter, with particular attention to avoiding cool-air drainage to one but not the other site.

Chemical fertility

The soil's macronutrient status should be assessed at planting time using methods that correlate well with crop nutrient availability. For example, nitrogen could be assessed with an incubation test, and phosphate with a bicarbonate or other weak extractant (Chang 1978).

The levels of plant and soil micronutrients are probably not worth including in a minimum data set. Deficiencies or toxicities should be corrected in the field first, and if this is not possible a minimum data approach should not be used.

The pH and salinity should be measured, but not if either is extremely unfavorable. The problem is not one to which the minimum data approach is useful.

Pests

Because rice pest observations would be extremely difficult on a routine basis, the minimum data system should be based as much as possible on the control of rice pests and diseases through host-resistance or cultural means.

Natural disasters

Floods or typhoons are not uncommon in some rice-growing regions and can cause major yield loss and deter farmers from using high levels of inputs. A minimum data system could be adapted for determining the success of treatments or genotypes in withstanding damage.

ORGANIZATIONAL ASPECTS

The mechanics of collecting and processing data from a large network of sites may present the greatest difficulty in establishing a minimum data system. If the organization is based solely on cooperation between regional research institutes, the task of handling and analyzing the combined data may fall unfairly on one institute. A better way is for a central institute to be primarily responsible for the analysis of the combined data from regional institutes and in ensuring standardized data collection methods. Because a network of stations in regions representing the full range of rice environments is needed, some institutes may need additional funds and resources.

Staff training may be necessary at some institutes because some of the measurements may differ from any made previously. Those responsible for data collection should be recognized by publication of the raw data, for example.

The task of checking and correcting errors in large data-collection exercises is the most time-consuming part of the whole analysis. Even before the project starts, forethought is needed about data checking, storage, and retrieval.

DATA ANALYSIS

Collection of a minimum data set is useful only if a systems approach in data analysis is envisaged. A systems approach implies the use of production models--either dynamic simulation models or static regression models--that take into account the effects of both environment and imposed treatments. The data to be collected must match the level of detail of the intended analysis. Factors that are most influential in determining yield should be measured in the greatest detail. The minimum data set proposed in Table 1 is intended to mesh with the model of rainfed wetland rice presented in this conference (Angus 1980).

DISCUSSION

The proposed minimum data system requires 1) consensus about data to be collected over a network of sites in diverse environments; 2) the establishment and maintenance of an intensive program of crop and environmental measurements; 3) a central system for checking, storing, and retrieving data; and 4) a method of analysis that can account for the data collected. The difficulties of establishing such a system must be weighed against the potential benefits. If the management of yield variability is judged to be of high priority and existing research methods are not making satisfactory progress, the minimum data system is recommended.

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Acquisition and analysis of rice and weather data

R. P. Sarker

The rice cropping practices in various Indian agroclimatic regions are outlined to delineate the factors limiting productivity. The methodology and the experimental layout used to acquire concurrent crop weather data at Indian stations are described and some improvements are suggested. Record-keeping requirements for meteorological and crop observations at various stations are briefly outlined. Experimental techniques on measuring evapotranspiration and percolation losses from rice fields are described. The different methodologies used in crop weather relationship studies in various countries and some results of such studies are briefly mentioned. Some results relating to crop yield formulation for forecasting yield from meteorological parameters, water needs of the rice crop, and the pre-disposing meteorological conditions that favor pest and disease outbreaks in India are detailed.

The pattern of growth and development of rice is strongly influenced by the variety and the environmental conditions under which it is grown. The sympodial component (tillers) is strongly influenced by cultural practices. The selection of agronomic practices must be preceded by an examination of the regional climatology and an evaluation of the meteorological requirements of rice.

The rice life cycle can be divided into the vegetative, reproductive, and ripening phases. The tillering stage of the vegetative phase is sensitive to temperature and photoperiod (Robertson 1975). In the reproductive phase, the time lag between panicle initiation and expression in thermosensitive and photoperiod-sensitive varieties is influenced by temperature and photoperiod, respectively. The duration of the ripening phase is affected by temperature (Robertson and De Weille 1973).

The rice organ-function system is strongly influenced by weather and climate and by the juxtaposition of environmental stresses to the crop stage function sensitive to them (Venkateswarlu 1977). The optimal values of rainfall, temperature, solar radiation, photoperiod, and relative humidity vary for the various phases. Owen (1971) gives the optimum air temperature range of rice as 20°C minimum to 30°C maximum. The optimum range of water temperature is 25°-30°C (Downey and Wells 1974a).

Solar radiation is one of the most important factors in predicting rice yields over a wide variety of locations (Van Ittersum 1971). Bright sunny weather during flowering is absolutely necessary as most of the grain yield in rice, like that in wheat, comes from postflowering photosynthesis. The radiation energy/sunshine hours accumulated during the 1 or 2 months preceding harvest, greatly influence final grain yield (Sato 1956, Aspiras 1964).

With the advent of modern photoperiod-sensitive varieties, photoperiod has become less important in rice culture. However, photoperiod-sensitive varieties may still be better suited to the natural trend of wet and dry seasons at specific sites.

Rice requires fairly high humidity for proper growth; flowering is best at 70-80% and will not occur below 40% relative humidity. Periods of high humidity with congenial temperatures may, however, trigger diseases and cause postharvest germination problems.

Wind is often considered unimportant in rice cropping; however, the waving

Meteorological Office, India Meteorological Department, Pune-5, India.

and fluttering of the canopy may interfere with photosynthesis. High winds may cause mechanical injury and affect reproduction by drying the ovary and blowing pollen off the stigma (S. Venkataraman, personal communication).

The anaerobic nature of rice poses special problems in water management. A flooded soil decreases the weed problem but causes water loss through percolation and evaporation. Rice is sensitive to the status of oxidized elements in the soil solution. Information on the water requirements of rice are often contradictory and excessive. The critical growth stages are tiller initiation, primordial initiation, and flowering (Gosh and Bhattacharjee 1959, Datta and Sen 1963, Sen and Datta 1967, Sreenivasan and Banerjee 1973, Subba Rao et al 1976).

CROP-WEATHER SITUATION IN INDIA

The extent to which the crop's weather requirements are met varies widely in India, and that gives rise to a wide variety of cropping practices and systems with an attendant impact on gross areal coverage, unit area productivity, gross outturns, and water-use efficiencies.

The monsoon breaks over southern India at the beginning of June and reaches the northern plains by 1 July. It begins to withdraw from the north by 15 September and from the south by the end of November. From June to October, the eastern part of the southern peninsula remains free of monsoonal activity. Thus, the monsoonal duration can vary from about 2 to 6 months.

Rice is the natural choice in monsoon areas where mean annual precipitation exceeds 100 cm, surface drainage is difficult, and water stagnation cannot be avoided despite percolation. However, the monsoon season's overcast skies and low maximum (25°C) and high minimum (20°C) temperatures in the vegetative phase are not conducive to optimum net assimilation and nutrient absorption. The strong winds hamper proper maintenance of leaf water regimes and crop fertility status. Water management is largely outside human control. Experimental evidence indicates that 130-day varieties are best (Tanaka 1964, Shastry 1975). Where the rainy season is longer than 100 days, medium-duration varieties are used to escape rainy weather, but they are less profitable. Short-duration varieties that take advantage of the long rainy season pose problems during maturity and storage of the first crop and ripening of the second. In northeastern India and in southwestern peninsular India, the torrential rainfall contributes to riverine flooding, which often inundates rice plants for a long time.

Better sunlight conditions for rice crop growth exist where the monsoon is absent or of only a short duration. As a result, higher yields are obtained in northwest India where irrigation facilities are available.

In the area where Southwest monsoonal activity is minimum, the entire clear season cannot be used for rice. Irrigation for nursery preparation depends on monsoon activity in the catchment areas. The delayed start of the season precludes the use of optimum duration varieties because the crop would mature during the retreating monsoon period. Severe cyclonic weather in the latter half of the monsoon's withdrawing phase poses great danger to standing crops in southern peninsular India. The main cropping strategy is to use short-duration varieties that can be harvested before the advent of the monsoon or optimum duration varieties that are planted a little ahead of the onset of the retreating monsoon. In this way, the crop is minimally affected by cyclonic weather, and flowering occurs after the cessation of rains.

Lower air temperatures are not congenial for rice set in November in northern India. The successive cropping of rice becomes limited in many areas. In east India where cool temperatures prevail, cold-tolerant varieties can help in raising a second crop following the monsoonal crop. In southern peninsular India where temperatures are warm in winter, a third crop planted in late winter and harvested in early or mid summer becomes possible. This crop grows under the best conditions for rice.

The above summary is the basis for delineating the following climatic zones for rice in India: 1) areas influenced by the retreating monsoon in which the premonsoon growing season is restricted by water availability, 2) areas influenced by a short northeast monsoon component and a full southwest monsoon component, 3) areas influenced by a reduced southwest monsoon component and a full northeast component, 4) areas with assured clear, bright weather for crop maturity during the southwest monsoon, 5) areas in which crops are chronically submerged by riverine flooding in the rainy season, 6) areas in which the postmonsoon season is too cold for rice, 7) areas in which the postmonsoon season is marginally cool for rice, and 8) areas with unlimited duration of the monsoon or postmonsoon season or both.

The varietal requirements for the various areas are discussed by Seshu (1973).

India thus offers the widest possible range of climatic conditions under which rice is or can be raised in Southeast Asia.

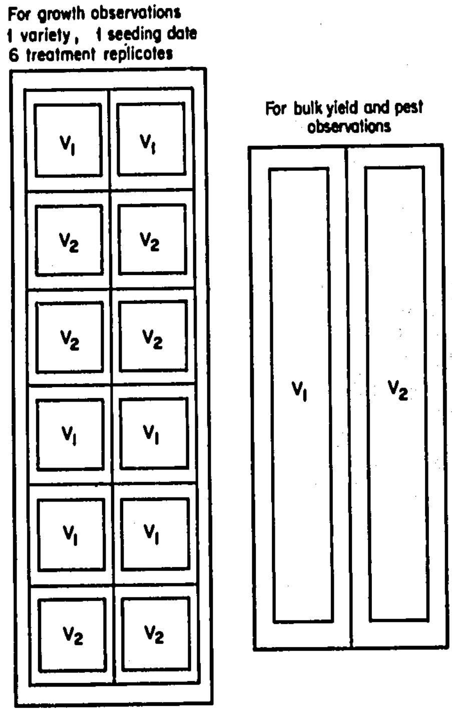
ACQUISITION OF CONCURRENT RICE-WEATHER DATA

Active interest in agricultural meteorology began in India in 1932. The Co-ordinated Crop Weather Scheme, initially sponsored by the Imperial Council of Agricultural Research began in 1945 to study rice, sorghum, and wheat. The aim of the Scheme was "the collection of systematic and detailed information relating to the weather as well as the life history of the crop during the growing season at selected experimental farms, according to a common plan".

Two rice varieties were raised simultaneously and weather observations were recorded at 0700 and 1400 hours local time at observatories on the farms. The calendar year was divided into standard weeks, numbered serially from the first week of January. The weeks were grouped into Standard Periods which constituted the grower's year.

Crop observations

The layout of the experiment for crop-weather study is shown in Figure 1. Assuming a 3-year rotation, blocks were set apart for periodical growth observations. Three blocks were set apart for recording bulk yields; another set were for recording the intensity of pest and disease attack which involved the removal of plants. The plots had a net area of 41 m^2 (excluding borders and irrigation channels). The arrangement was designed according to the paired plot technique to provide a 4-plot contiguous area per variety for recording microclimatic observations. The sampling unit for broadcast rice was a square frame 0.6 m x 0.6 m. For



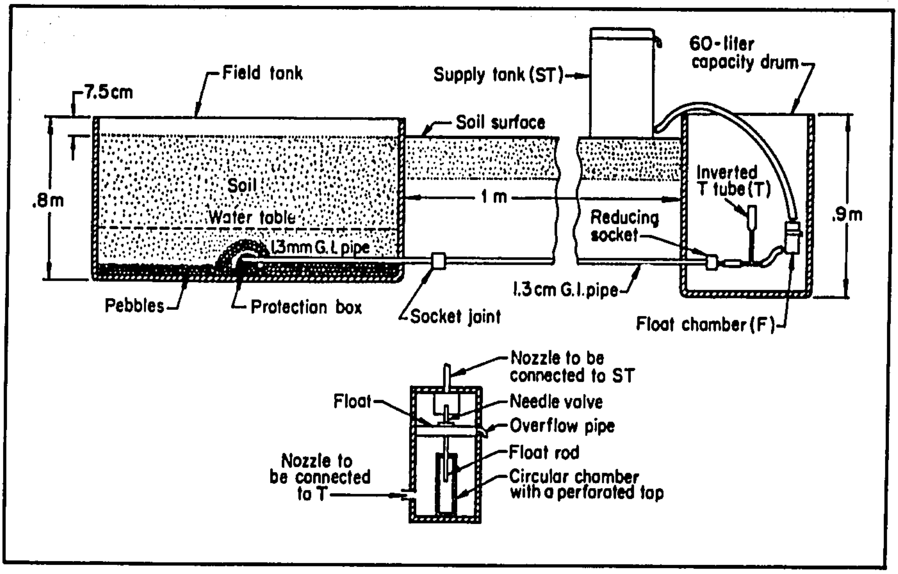
1. Crop layout (India Meteorological Department).

transplanted rice, each sample consisted of 3 hills from each of 2 adjacent rows. Using Tippett's Random Numbers, 3 samples were chosen from each subplot, giving a total of 36 samples for the 6 replications of each variety.

Observations were made on survival count after transplanting, number of culms (tillers), height of the tallest culm in the hill, and number of panicles. All observations were made weekly except survival count and number of panicles, which were taken daily in the initial and final crop stages. Yield as determined by sampling, total plot yield, weight of 1000 grains, protein content, and grain moisture percentage were also recorded. The percentage and intensity of pest attack were recorded by specific sampling. The effects of pests on growth and yield were also noted.

Meteorological observations

The meteorological observations recorded in observatory plots near the crop blocks included those on rainfall, air temperature, relative humidity, soil temperature and moisture, wind, evaporation, cloudiness, sunshine hours, and the incidence



2. Volumetric lysimeter method.

of special weather phenomena. Dry and wet bulb temperatures at ground level and at 6", 12", 24", 48" above ground were recorded by Assmann psychrometer at 0700 and 1400 hours at the center of the observatory enclosure and in the center of the 4 adjacent plots of each variety.

Evapotranspiration measurements

For measuring evapotranspiration (ET), percolation losses, and ineffective rainfall, Dastane et al (1966) advocate the use of 3 containers of about 160 liters capacity and 100 cm height. Two tanks do not have bottoms. They are buried so that 20 to 25 cm protrude above the soil. For ensuring proper microclimate the field tanks have to be placed in the center of a large rice field. The daily difference in water levels, between tanks A and B furnish percolation values. Differences in consecutive readings of container A give ET losses. The difference between total rainfall and water level in container C gives ineffective rainfall.

The drum culture technique is not suited to study the ET losses of the rotational, aerobic rice crops. Therefore, the volumetric lysimeter system was used for measuring ET losses of irrigated crops (Venkataraman 1956, 1961) and consisted of a field tank 1.2 x 1.2 x 0.9 m sunk in the middle of a well-exposed field and back-filled with soil to maintain the same soil profile as in the field (Fig. 2). A water table can be maintained in the field tank both above and below the soil surface as desired. This arrangement ensures that, where necessary, the same lysimeter can be used to study the ET of an aerobic crop taken up in rotation with paddy.

With the volumetric lysimeter, losses from surface water due to ET are made good by that flowing from the reservoir tank through the float chamber. Any rainfall that tends to raise the water level drains through the outlet in the float chamber and can be collected and measured. The ET for the paddy crop is given by the amount of water lost from the reservoir tank *plus* rainfall *minus* the amount of overflow, if any.

Percolation losses were measured with a bottomless rain gauge. When installed in the field with its rim 10 cm above the water surface, perforations on its body remained under water. The drop in water level was measured by a suitable hook gauge. The percolation gauge can be set near the bund; however, a sufficiently large guard tank is necessary to prevent vitiation of readings through surface inflow from surrounding fields.

Pest observations

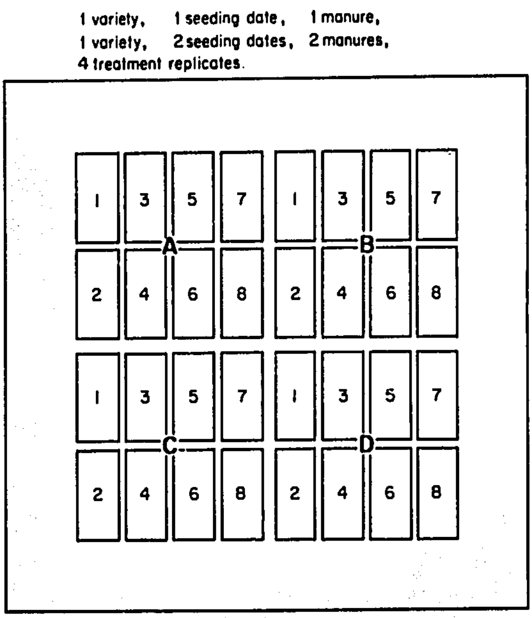
The intensity and percentage of systemic infections were estimated by removing plants. The observations were recorded in separate blocks. Statistical procedures for assessing the percentage of affected plants and the intensity of affliction were ascertained by specific observational methodology for each pest.

LIMITATIONS OF PRESENT SCHEME AND SUGGESTIONS FOR IMPROVEMENT

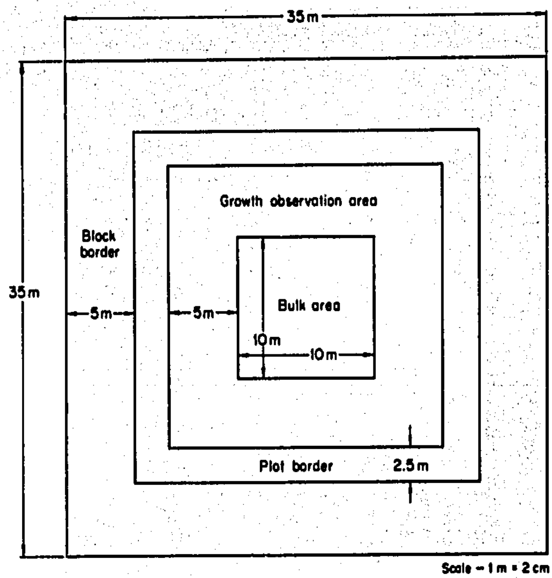
In the Indian experiments, the data series for any given station were limited because a single seeding date was used in a season. Data from different stations could not be pooled because soil types and agronomic treatment varied. The treatments involving two varieties for crop weather trials were distributed in small plots (Fig. 1). For the international experiments suggested by World Meteorological Organization, the treatments consisting of variations in varieties, seeding dates, and manuring were distributed in small plots (Fig. 3). Crops in small plots do not enjoy a natural microclimate; later crops are affected by an earlier stand. The main reason for randomization in small plots is to account for fertility variations.

The following improvements were suggested (Venkataraman, personal communication):

- Collect observations of a common variety or similar varieties seeded at different times at a number of sites in a homogenous soil zone.
- Raise crops in large plots after building up the fertility status of the entire experimental area to above-optimum levels.
- Supplement detailed observations at a principal station by a restricted range of observations at ordinary and auxiliary stations in a soil zone.



3. Crop layout (WMO).

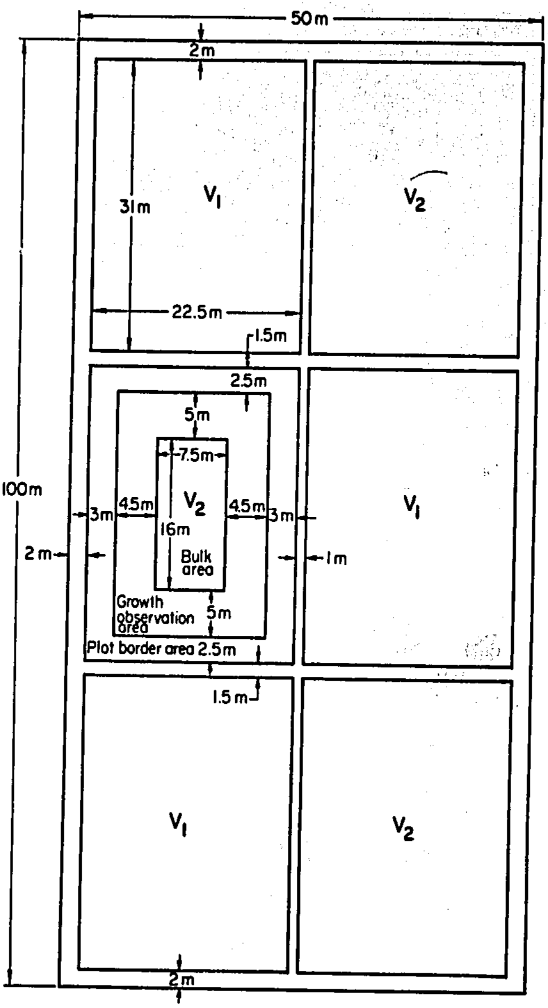


4. Proposed monoblock layout.

A sample layout meeting the above requirements is given in Figure 4. A similar layout adopted by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) for their Jowar-Weather modeling is given in Figure 5. The central core of these layouts can be used to determine bulk yield and to record observations that don't disturb the crop. Destructive observations are recorded in the block border. Growth and soil moisture observations are recorded in the area adjacent to the central core. In these trials the crop is reasonably protected against pests.

Each soil zone should have one principal station, two ordinary stations, and five auxiliary stations. At the principal station, three varieties sown on three different dates may be observed. At the ordinary station, the most prevalent variety seeded on three different days may be studied. And only the most prevalent variety sown on the optimum date should be observed at an auxiliary station.

At the auxiliary station, only routine meteorological data on air temperature, humidity, wind, and pan evaporation, are recorded by eye reading instruments.



5. Layout for crop weather modeling experiment in red soil, International Crops Research Institute for the Semi-Arid Tropics, 1979 kharif sorghum. V_1 = CSU-1; V_2 = CSA-6.

The crop observations may include height, number of tillers, number of leaves, date of emergence, and commencement and end of tillering and flowering.

At an ordinary station, besides eye reading observations, data may be recorded with thermograph, hygrograph, pluviograph, and sunshine recorder. Additional crop observations may include determination of leaf area index and net assimilation rate.

At a principal station, all the observations routinely made at the ordinary station, with the addition of radiation and soil moisture fluxes, and soil and water temperature regimes, may be collected. Profiles of field capacity, permanent wilting point, bulk density, and soil moisture are recorded before sowing and after harvest.

ANALYSIS OF RICE-WEATHER DATA

In order to forecast rice yields based on weather, it is necessary to understand the relationship between crop growth and the environment, to identify the meteorological conditions that favor pest outbreaks, and to determine rice water requirements for irrigation scheduling in different climate zones.

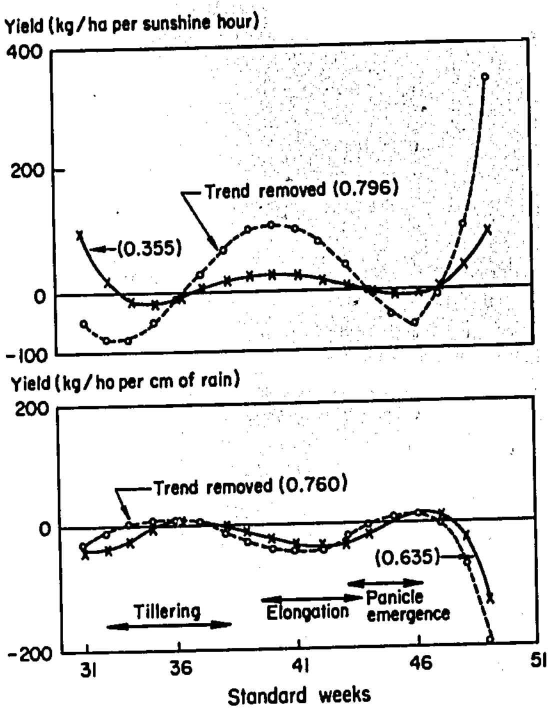
Crop weather relationship and crop yield formulation

The Crop Weather Analysis Model, the Empirical-Statistical Model, and the Crop Growth Simulation Model (Br .er 1977) have been used to study crop weather relationships for wheat, but little research with these models has been done for rice.

Fisher's Response Curve Technique (Fisher 1924) has been used by Indian workers to understand the influence of various meteorological parameters on rice yield. For Karjat Station (18° 55'N 73° 18'E) Sreenivasan and Banerjee (1973) found that the primordial initiation is a critical growth stage for water needs, and that rainfall during the maturity phase depresses yield. Huda et al (1975) found that rainfall at maturity is beneficial in upland paddy but harmful during the vegetative phase. Above average daily maximum and minimum temperatures are beneficial during the seedling stage.

The Curvilinear Technique has been used to find out the optimum values of weather elements during a particular crop phase and to predict the crop yield.

The preceding two methods were used by Sarker (1978) to study the effects of meteorological and other derived parameters on autumn rice yields at three experiment stations in India. The effect of maximum temperatures on rice yield was found to be more prominent than the effects of rainfall and humidity. Maximum temperatures are important from transplanting to tillering. Relative humidity has a significant positive effect at tillering, and rainfall acts negatively at elongation (Fig. 6). The soil moisture storage, Thornthwaite Moisture Index, and Growing Day Degree during July and August had

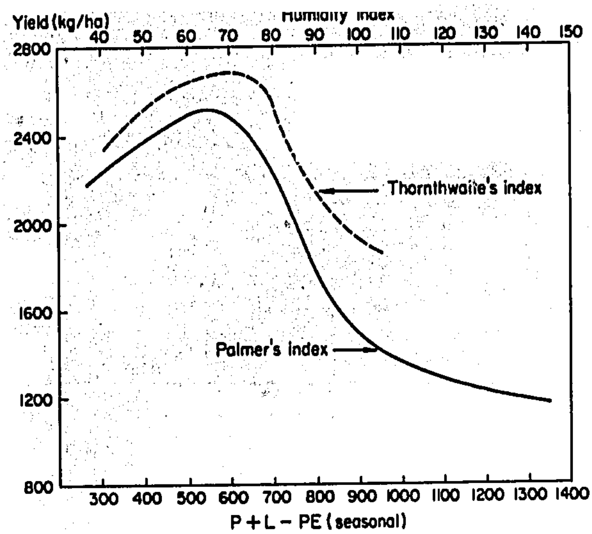


6. Response curves, Chinsurah paddy Bhasmanik.

significant positive correlation (Fig. 7, 8).

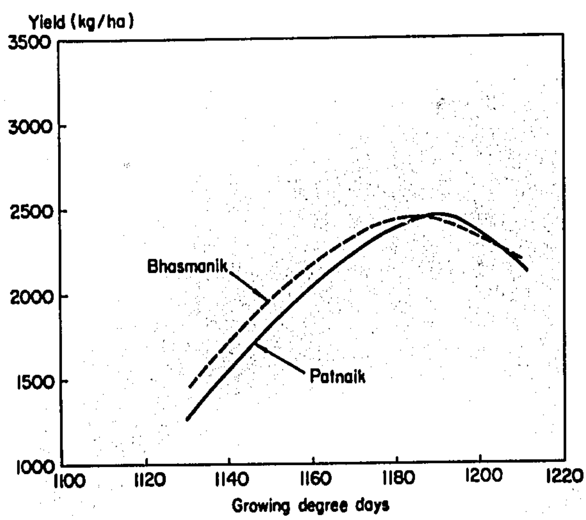
In studies of the relationships between rice yield and biometric characteristics, about 50% of the yield variation in paddy could be accounted for by factors such as plant population, number of tillers per plant, height of the mean tiller, and length of the ear head.

Murata (1975) reports that considerable work has been done with statistical and simulation models in Japan to find the effect of climatic factors on rice yield. Correlation studies carried out at various locations in central and southern Japan showed that solar radiation or sunshine hours are the limiting factors from booting to active grain filling. In the north mean air temperature was the major limiting factor during the same period. Physiological knowledge and experimental data supported the regression models. Several recent dynamic models that predict yields using plant factors and air temperature and solar radiation data for grain-filling period show good fit with actual rice yields in Japan.



7. Variability of yield with respect to Palmer's and Thornthwaite's indices for variety Bhasmanik at Chinsurah, India.

At the national and international level crop-weather relationship studies may help plan the procurement and distribution of food. In the regression technique used for crop yield forecasting, the yield per unit area is taken as the dependent variable and meteorological factors such as rainfall and temperature for overlapping periods ranging from 7 to 60 days are treated as independent variables. The statistical methodology first identifies meteorological factor periods that correlate significantly with crop yields. These periods are screened again keeping



8. Variability of yield with respect to growing day degree fo varieties Patnaik and Bhasmanik at Chinsurah, India.

in view the critical periods in the life cycle of the crop for the factor in question. The weather factors and periods that have significant association with crop yield are then combined to derive linear regression equations from which future yields could be forecast. Another factor, termed *technological trend*, is also considered in the Regression Model. It represents the recent spurt in yield due to advanced agronomic practices, high yielding varieties, and better management. Using data from *crop outturns*, rainfall statistics from a network of more than 4,000 rain gauge stations, and meteorological parameters from observatory stations, formulas to forecast rice yields for major rice-producing areas in India have been developed. For example, Das and Mehra (1971) using 30 years' data developed the following regression equation for the subdivision Gangetic West Bengal:

$$X_1 = 668.76 + 17.61 x_2 - 134.42 x_3 + 11.33 x_4 + 15.25 x_5$$

where, X_1 is the expected yield,
X_2 is rainfall in June (inches),
X_3 is occasions of drought,
X_4 is the number of rainy days from 16 September to 15 October,
and X_5 is the trend.

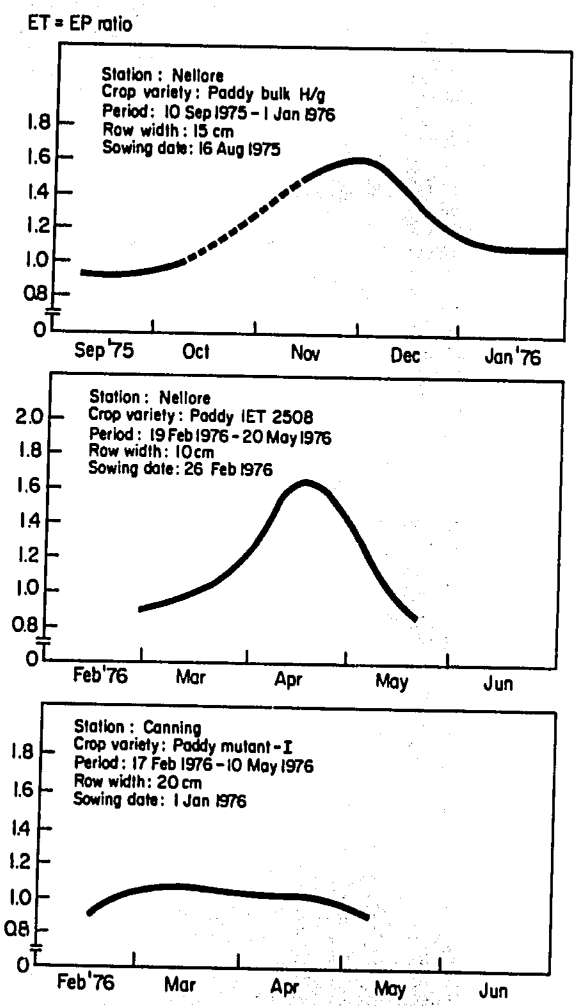
A rainy day is counted as one with 10 cents (0.1 inch) or more of rainfall in a day. Occasions with drought are counted from the number of consecutive days with less than 10 cents of rain and coded as follows:

7 days ... Code 1
8 to 14 days ... Code 3
15 to 21 days ... Code 6
22 days or more . Code 10

The regression was seen to account for 77% of the annual yield variation.

Evapotranspiration of rice

Lysimetric estimates of rice ET were made for a humid station (Canning) at 22°30'N and 88°40'E and a semiarid location (Nellore) at 14°27'N and 79°59'E (Subba Rao et al 1976). At Canning, the ratio of ET to pan evaporation (EP) was 1.0 throughout the crop life period from sowing to harvest. However, the ET-EP ratio at Nellore shows a progressive increase to 1.5 until 50% flowering. From this peak value, the ratio declines sharply and remains at 1.0 until harvest. These observations indicate that the peak water need of the rice crop and the degree of senescence may vary with variety (Fig. 9).



9. Ratio of evapotranspiration (ET) to evaporation (EP).

Pests and weather

The factors involved in insect-plant environment interactions are extensive and, therefore, require vast amounts of specific field data under various environmental conditions over many years. Attempts to delineate meteorological conditions conducive to the outbreaks of important pest activities have been based on single-station observations.

Blast of paddy - Pyricularia oryzae. Padmanabhan et al (1971) found that a low minimum temperature below 26°C together with relative humidity 90% and above are favorable conditions during any susceptible growth stage. Infection was higher when the minimum temperature dipped lower to 20°C.

Yellow stem borer-Tryporyza incertulas. Studies at Central Rice Research Institute, Cuttack, indicate that unusually low temperatures (especially below 29°C) in May and June encouraged ovipositing by the yellow stem borer moths. Maximum moth emergence and abundance occurred when the daily mean minimum air temperature ranged from 16° to 27°C, and the mean maximum temperature ranged from 28° to 37°C. The soil temperature at the 5-cm depth ranged from 19° to 30°C. Emergence ceased, howe`r, when the mean daily minimum tempe ure fell below 14°C. Prakasa Rao et al (1971) noted that a steady rise in soil temperature to 19°C triggered moth emergence from overwintering larvae. They concluded that the soil temperature at 5 cm depth was a dependable parameter for predicting the onset of moth emergence.

Gall midge-Pachydiplosis oryzae. Light-trap data collected over 16 years at Cuttack showed that gall midge was active from the end of September to the end of October when hot humid conditions, a mean maximum temperature of 31°C, and a relative humidity of 84% prevailed. When the premonsoon showers were below 250 mm in May and June, however, the pest was delayed. Early showers ushered it in. The infestation increased when August had 24 rainy days and September had 18, and when there were less than 4-6.5 sunshine hours/day.

Rice hispa-Dicladispa armigera. A 17-year (1947-63) study by Prakasa Rao et al (1971) revealed that hispa epidemics were associated with heavy rainfall in July followed by unusually low rain in August and September and the consequent large number of hours of bright sunshine. Steady temperatures during these months seem favorable for hispa's active feeding and breeding.

Leafhopper Nephotettix apicalis, green jassid. Studies by Sathpathy and Maiti (1973) on the seasonal variability in population density and distribution of rice hoppers show that frequent and heavy monsoon showers between July to September do not favor the development of the pest population. Population increases occur in the fields after the monsoon rains, from early October to mid-December when the temperatures vary from 14° to 34°C and relative humidity is from 65 to 98%.

The Gundy rice bug-Leptocorisa varicornis Fabricius. Srivastava and Saxena (1964) reported that late planted early rice varieties and early planted medium varieties are usually susceptible to heavy infestation by the Gundy rice bug. Ghose et al (1960) found that temperatures of 27°C - 28°C and a relative humidity greater than 80% favor this bug. Although active during cloudy weather, downpours wash away the young nymphs.

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III. Research and applications

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Application of agrometeorology to some aspects of rice research in Sri Lanka

C. R. Panabokke and N. Hussan

Sri Lanka exhibits a very distinctive seasonality and range of agroclimatic features because of both its particular location in the Indian Ocean and its position within the intertropical convergence zone.

Superimposing the agroclimatic divisions of Sri Lanka on its general soil map, 24 agro-ecological regions are identified. Rice is grown in 18 regions, representing a wide range of environmental conditions.

Long-term agrometeorological data are presently available for 18 agro-ecological regions. Maximum and minimum air temperatures, relative humidity, sunshine hours, open-pan evaporation, wind velocity, soil temperatures at different depths, and some solar radiation data are included.

The sowing-to-harvest duration of the rice crop in the different agro-ecological regions is primarily governed by the bimodal rainfall seasonality and the resulting soil hydrology of the inland valley systems in which a greater part of the country's rice is grown.

Rice breeding and agronomic research aim to match the different growth phases of the rice plant to the seasonal sequential rhythm of the environment, with a view to capturing maximum benefits from those environmental factors that strongly influence the respective yield components. This is discussed in relation to specific situations that are encountered in five agro-ecological regions.

In the Sri Lankan environment, the seasonal rainfall patterns as well as rainfall variability exert a major influence on rice yield and performance. It is now increasingly recognized that in some Sri Lankan rice-growing environments, the amount of solar radiation especially during rice's reproductive phase could limit the attainable yields.

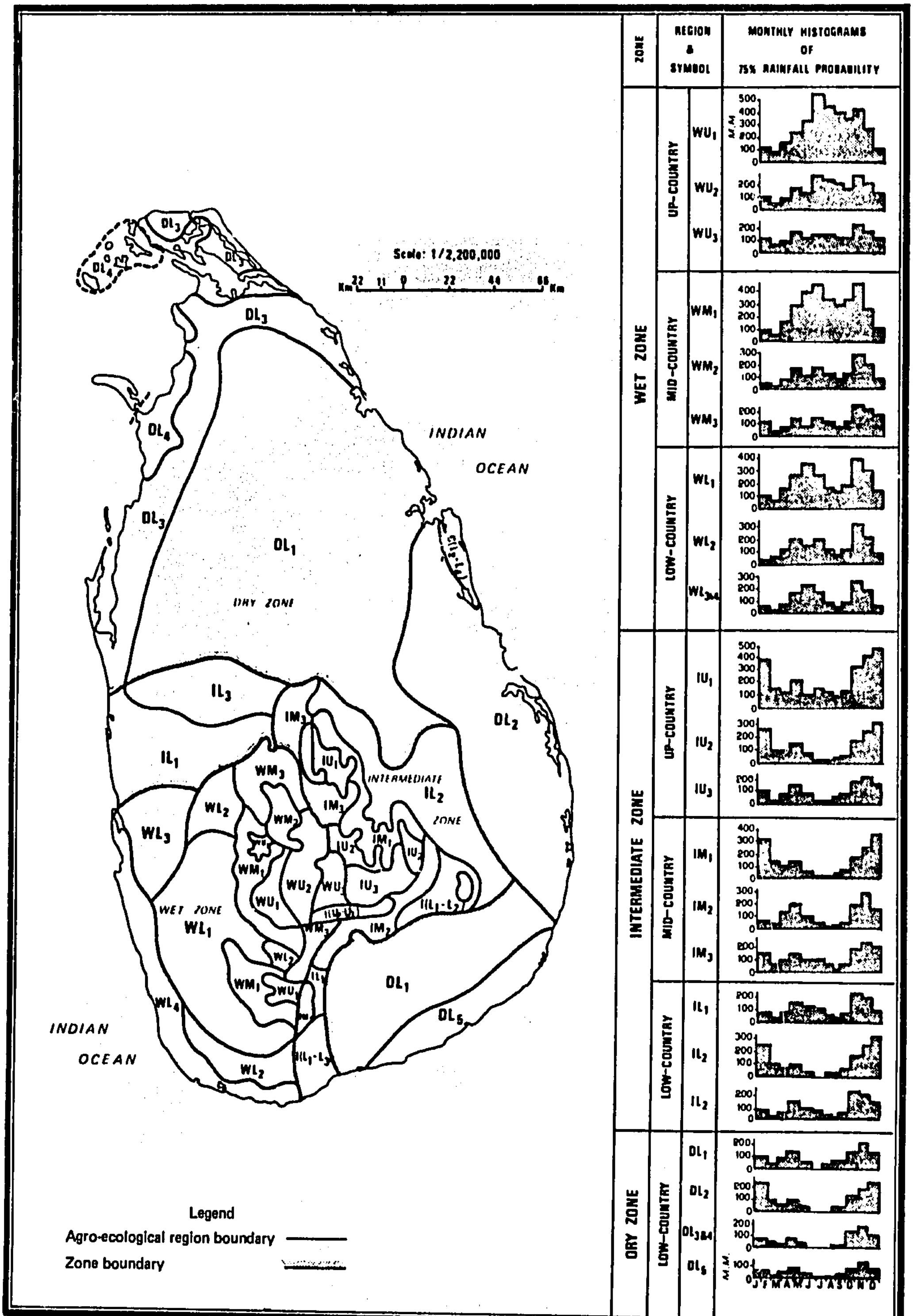
The annual rainfall distribution in Sri Lanka exhibits a very distinctive seasonality because of the country's particular location in the Indian Ocean and its position within the intertropical convergence zone. The rainfall over most of the country follows a well-expressed bimodal pattern. The mean annual rainfall ranges from 1,000 mm in the semihumid to dry regions to 5,000 mm in the very wet regions.

On the basis of rainfall, vegetation, soils, and present land use, the country can be divided into the wet, intermediate, and dry agroclimatic zones. Within the wet and intermediate zones, a subdivision based on elevation takes into account the temperature limitations for the more important crops: land below 300 m is low-country, that between 300 and 1,000 m is mid-country, and that above 1,000 m is up-country.

The agro-ecological map of Sri Lanka (Fig.1) shows the country's 24 agro-ecological regions and their respective annual sequential rainfall probability histograms. The criteria for identifying and demarcating these agro-ecological regions have been described by Panabokke and Kannangara (1975).

The fact that rice is grown in 18 of the 24 agro-ecological regions is a good index of the wide range of environmental conditions under which it is cultivated in the country. The sowing-to-harvest duration of the rice crop in the different agro-ecological regions is primarily governed by rainfall seasonality and the resulting hydrology of the rice lands in the various inland

Department of Agriculture, Peradeniya, Sri Lanka.



1. Agroecological regions of Sri Lanka.

valley systems described by Panabokke (1978).

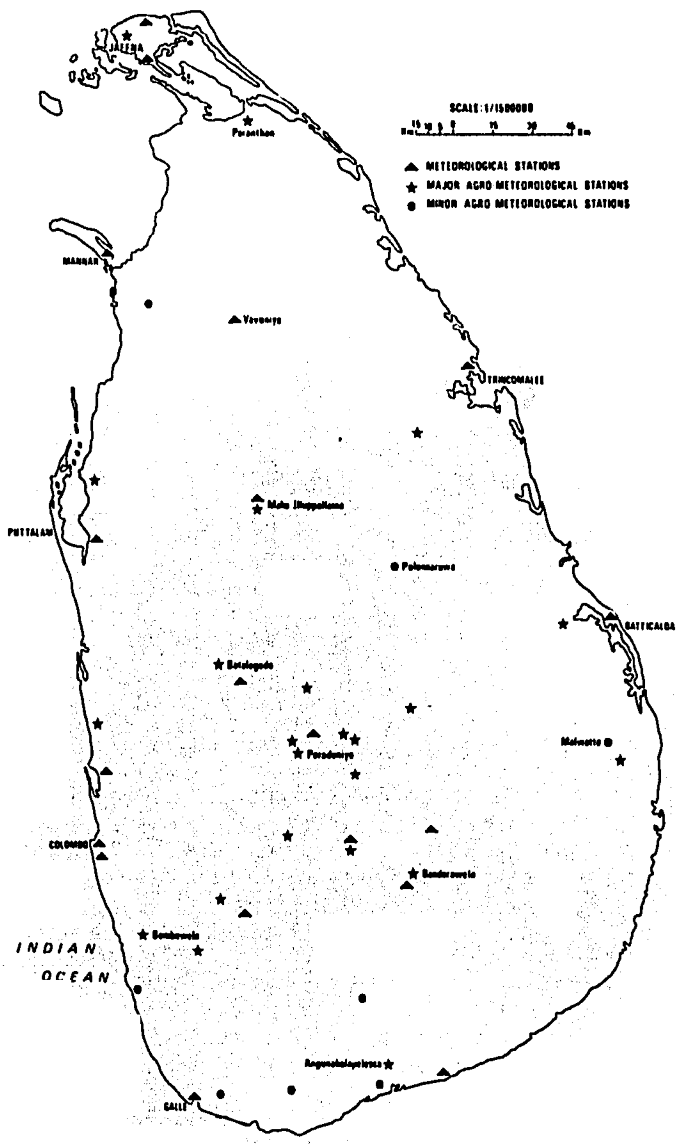
Usually, two rice crops of 3 1/2 to 4 1/2 months duration are grown in the phreatic rice lands of most parts of the wet zone. In the fluxial rice lands, the rice crop is usually in the 5- to 6-month age class. In the dry and intermediate zones, the major rice crop is grown during the main rainy season from October to February, while a shorter duration crop is grown where irrigation water is assured during April to July. There is no temperature limitation for rice growth in the low- and mid-country.

In the up-country, the cold temperatures during November to January preclude rice cultivation. Instead, a single crop is grown from February to July.

PRESENT STATUS OF AGROMETEOROLOGICAL DATA

Daily rainfall data are available at 650 rainfall stations scattered throughout the island. Record-keeping ranges from 110 to 25 years. Monthly histograms of rainfall expectancy at the 75% probability level have been prepared for 381 stations.

The Department of Meteorology maintains 20 meteorological stations, which have been functioning since 1911. Available long-term data give daily



2. Agrometeorological and meteorological stations of Sri Lanka.

maximum and minimum temperatures, relative humidity, and sunshine hours. Some stations have short-term records of wind velocities.

The Agriculture Department and the Plantation Crops Institute have maintained agrometeorological stations for periods ranging from 25 to 40 years. In 1974, under a United Nations Development Program-sponsored project, 20 new stations were set up in selected agricultural research institutes and stations distributed over the island (Fig.2).

Long-term agrometeorological data are presently available for 18 agro-ecological regions. Maximum and minimum air temperatures, relative humidity, sunshine hours, open-pan evaporation, wind velocity, soil temperatures at different depths, and some solar radiation data are included.

Okamoto (1976) documented detailed agrometeorological data on the rice crop in three rice-growing locations during 1973-75.

A more organized and systematic interpretation of this significant body of agrometeorological data is needed to efficiently service agricultural research and development.

SOME APPLICATIONS OF AGROMETEOROLOGICAL DATA TO RICE RESEARCH PROGRAMS

Rice agronomic research aims to match the growth phases of the rice plant to the seasonal sequential rhythms of the different agro-ecological regions, with a view to capturing maximum benefits from the environmental parameters that strongly influence the respective yield components.

By using traditional patterns of rice cultivation, farmers have adjusted the age classes of rice varieties to the simple technologies of land preparation, sowing, and harvesting. The improved technologies for speedier land preparation, and improved irrigation and fertilizer use provide greater flexibility in selection of planting times and crop duration.

Specification of the environment is, therefore, an essential prerequisite that enables the rice breeder to tailor the different growth phases of his varieties to the sequential components of the environment. A specification of the variability of the individual environmental components between seasons is also essential.

The foregoing considerations are applied to specific situations in five agro-ecological regions.

Dry zone, low-country; agro-ecological region DL_1

Through years of empirical observation farmers of agro-ecological region DL_1 have determined that the first week of October or the 40th week is the optimum time for sowing traditional rice on pluvial land. The subsequent rains always ensure crop growth and development up to flowering (Fig.1). Crop failure is normally associated with drought during postflowering after the 50th week. Matching the crop water requirement of a dryland rice crop against the 1:1 confidence limits of expected rainfall has demonstrated that rice of the 3- to 3 1/4-month age class has a greater chance of success in this environment than the traditional 4-month rice (Panabokke and Walgama 1974).

Sri Lanka's present breeding program for dryland rice is designed to evolve varieties in the shorter age classes. However, the threshold yield level for a 3 1/4-month age class rice cultivar, for example, is usually around 2 to 2.5 t/ha because the reproductive phase coincides with the periods of lowest solar radiation (Table 1) and low maximum temperatures (Fig.3).

Intermediate zone, low-country; agro-ecological region IL_1

The main rice crop in agro-ecological region IL_1 is grown on phreatic lands from October to January. Rainfall and other environmental conditions are satisfactory for the 4-month rice during this season. A second rice crop is grown from April to late June. Rains during this period are highly variable, but solar radiation and temperatures are satisfactory for good growth (Fig.3,4). However, the soil moisture in some years could be marginal for the traditional 3- to 3 1/2-month cultivars. The present rice breeding program is, therefore, experimenting with the 75- to 80-day age group to reduce farmers' risk during this season.

Wet zone, low-country; agro-ecological region WL_4

The main rice crop in agro-ecological region WL_4 is grown on both phreatic and fluxial lands from October to

Table 1. Monthly average solar radiation in Sri Lanka.

Site	Av solar radiation (cal/cm^2 per day)												Years (no.) covered
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Maha Illuppallama DL_1	377	433	417	395	340	353	371	368	395	362	363	290	10
Batalagoda IL_1	373	401	399	351	321	321	320	330	336	317	345	352	5
Bombuwela WL_4	385	381	338	408	343	343	321	335	338	335	336	340	5
Peradeniya WM_2	379	401	396	358	352	307	352	315	312	331	329	318	6
Bandarawela IU_3	341	414	459	341	331	384	347	364	356	263	280	240	4

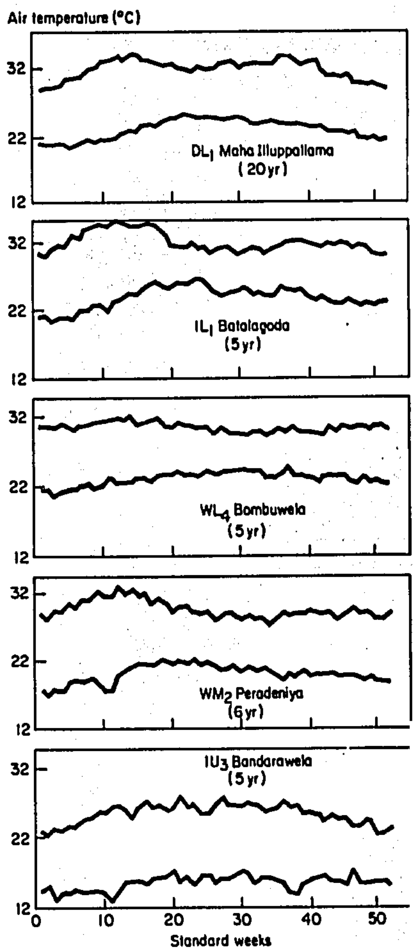
January. On fluxial land, a 5-month rice is able to exploit the higher solar radiation during January-February that coincides with reproduction and ripening.

The second rice crop, grown from April to July, is subject to certain environmental stresses that produce a high percentage of sterility during some years. Low diurnal temperatures (Fig.3), and great variability of solar radiation may be partly responsible for this sterility, but further studies are needed.

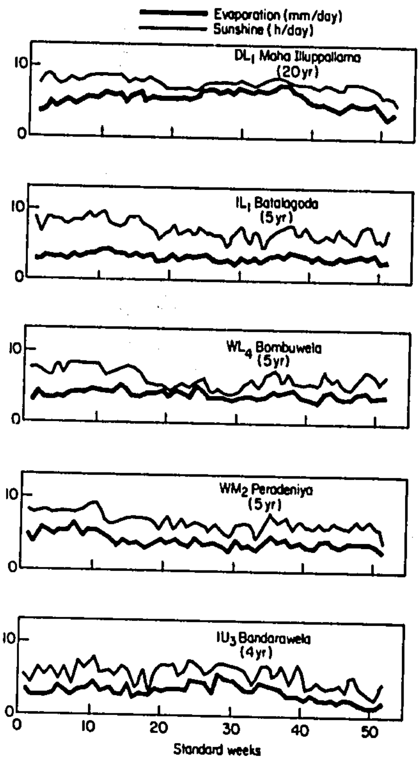
Wet zone, mid-country; agro-ecological region WM_2

The main rice crop in agro-ecological region WM_2 was traditionally a 5- to 6-month rice grown from July to January. This has now been replaced by 4- to 4 1/2-month cultivars grown from October to February. The low solar radiation during late October through mid-December (Table 1) is one major environmental constraint to high yields in this season. Furthermore, in some years the minimum air temperatures during the first 3 weeks and last 2 of the year (Fig.3) could drop to just below 15°C for a few days causing some sterility in the rice crop. Further observations are needed to work out the probabilities of such occurrences.

In the inland valleys, rice oriented to the north-south direction yields lower than that oriented to the east-west.



3. Weekly averages of maximum and minimum air temperatures in Sri Lanka.



4. Weekly average evaporation and bright sunshine hours in Sri Lanka.

Field measurements reveal that the total daily solar radiation received in the north-south oriented inland valley is around 20% lower because of shading by adjacent elevated parallel ridges that characterize this landscape.

Intermediate zone, up-country, agro-ecological region IU_3

Weerasinghe and Jeyendran (1979) have reported the effects of environment on rice yields in agro-ecological region IU_3. The minimum air temperatures range from 12° to 14°C during January through March, and 15°to 17°C from April through December (Fig.3). Maximum air temperatures are generally below 25°C from October through February, and 25°to 27°C from March through September.

Rice is usually transplanted during February-March and harvested during July-August. In this environment the age of the rice cultivars commonly grown in the other parts of the country is extended by about 4 to 5 weeks; the period from flowering to harvest is extended by about 6 to 7 weeks. While the diurnal range of temperatures plays a significant role in the growth of the rice plant, grain production is influenced more by optimum levels of maximum and minimum temperatures at flowering time.

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Agrometeorological research and extension for the rice farmer in the humid tropics

M. W. Baradas

A program of climate-based agrotechnology (CLIMAT) is proposed for the humid tropics. CLIMAT encourages farmers to control water availability rather than gamble with rainfall variability. It also mobilizes the abundant human capital in the region, which is idle during the dry season.

Agrometeorological guidelines for the development of CLIMAT are given. Agroclimatic zonation, an early stage of CLIMAT, and the sunshine-based cropping and weather-based crop protection systems, representing an advanced stage, are discussed.

A recommended baseline package of CLIMAT should be improved with farmers' comments and validated at representative sites in the humid tropics.

This paper analyzes climate-related food production problems and prospects for *rice farmers* in the humid tropics. As used in this paper, the term rice farmers means those who grow at least one crop of *dryland* or *wetland* rice per year. In South and Southeast Asia alone, some 50 million hectares were planted to *dryland* and rainfed *wetland* rice in 1973-75 (Barker and Herdt 1979). Harnessing the climate will help farmers profitably grow at least two crops of rice per year or grow other crops either before or after rice or both. This additional production will greatly alleviate the region's food shortage problems. In discussing the issue, we recognize that farmers want increased return to their labor and investments, and not simply increased yield.

Agrometeorological research covers the activities and information output of individuals and agencies concerned with the relation of climate to crop production. Agrometeorological extension generally refers to the activities of agencies or organizations that explicitly aim to harness the climate to promote the well-being of farmers.

CLIMATE-RELATED PROBLEMS OF RICE FARMERS IN THE HUMID TROPICS

Rainfall variability, flood, and drought

Rather variable rainfall distribution in the humid tropics is not necessarily more variable than in the temperate zones (Fukui 1979). Serious fluctuations in the region's food production occur since the bulk of the crop area is rainfed. Flood and drought are the recurrent problems reported in *Food Outlook*, a publication of FAO's Global Early Warning System on Food and Agriculture. Both are major constraints to high yields on Asian rice farms (IRRI 1977).

The Green Revolution assumes that water is a given rather than a limiting factor for rice production. Adequate water control is clearly a precondition for improved rice production using "miracle varieties" (IRRI 1978a, b; Swaminathan 1979).

It has been suggested that research emphasis on the problems of rainfed rice in Asia, instead of on irrigation, will increase production and result in greater total benefits (Barker and Herdt 1979). In the Asian cropping systems network

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(Carangal 1977), priority is on rainfed areas and those irrigated only during the rainy season. Instead of improving the poor water supply, which is the basic problem, the network simply accepts it.

Cropping patterns in rainfed areas are usually rationalized on the basis of rainfall expected at given probability levels. The monthly rainfall that is likely to occur in 3 out of 4 years has been suggested as a practical and realistic value (Oldeman and Suardi 1977). The recommended cropping patterns make the farmers gamble with the weather. The idea of losing once in 4 years is more than enough for many small farmers to discard the recommended "rainfall-gambling technology", especially if the loss occurs in the first trial.

Water insufficiency is the basic problem. The solutions so far provided involve sophisticated techniques for predicting the amount and date of water insufficiency.

Low sunshine and other difficulties during the rainy season

Crop yields, as well as employment and income, particularly of small farmers, *will likely continue to be low and unstable,* even if floods are minimized and rainfall is well distributed, *as long as the rainy season is considered the main growing season in the humid tropics.* In this paper, the practice of growing annual crops in the rainy season is referred to as the *rainfall-based cropping system.*

Cloudiness in the rainy season reduces the sunlight available for photosynthesis. According to Yoshida (1978), the average solar radiation received in the Philippines is about 367 cal/cm^2 per day in the rainy season (July-November) and 463 cal/cm^2 per day in the dry (January-May).

There are also more insect pests largely because of favorable conditions, more weeds because water is everywhere, and greater disease incidence due to high humidity. Crop protection is more expensive because there are more alternate hosts and sprayed chemicals are often washed off by rain.

Most of the typhoons in the typhoon belt of the humid tropics have damaging winds and floods in the rainy season. Between 1968 and 1975 in the Philippines, about 295,000 t of rough rice were lost annually to typhoons and floods (Baradas 1978a).

Farm machinery, important to intensive crop production, bogs down in soggy fields.

Transport of production inputs and harvest grain is a particularly acute problem in the rainy season where the farm-to-market road network is poor.

Grain drying is more expensive in the rainy season because of low sunshine and high humidity.

DESIRABLE THRUSTS IN AGROMETEOROLOGICAL RESEARCH AND EXTENSION

Divergence of current research and extension objectives

The ultimate objective of agricultural (including agrometeorological) research should complement that of agricultural extension. So far, it has not done so. The general objective of agricultural research is to develop techniques and products that will increase the food supply. The objective of agricultural extension is to improve the well-being of farmers.

The objective of self-sufficiency in food has been given great attention in several countries. However, national food sufficiency does not necessarily mean that the small farmers, who are supposed to produce at least their own food, have an adequate food supply.

Inherently, the two objectives appear compatible. Divergence occurs when an adequate food supply must be attained in a very short time. The technology used to produce quick results requires expensive inputs and entails great risks. The small farmers, who have neither the resources nor the capacity to shoulder the attendant risks, are naturally left out. In advanced agricultural development, divergence apparently occurs because highly efficient crop production is emphasized. In line with this thinking, the fewer the farmers who produce the nation's food, the better.

Extension programs have helped improve crop production at the expense of small farmers. Farming innovations have often been introduced first to the so-called "early adopters," who are usually the "big farmers." This practice demonstrates to the "small farmers" that the innovation works and thus gains time for promoting the given innovation. But the time so gained is often used to introduce another innovation to the big farmers. Attainment of impressive national food statistics has been easier and faster when the meager resources of the extension service are concentrated on programs for the big farmers.

Modern agrotechnology has led to the present world situation where millions of people die of hunger in spite of impressive food supply statistics. The technology requires resources and risks that only the big farmers can afford and produces food at a cost beyond the reach of the majority.

Converging research and extension

A desirable technology should require inputs which small farmers can provide with minimal assistance from external sources and with minimum risk. The yield may not be as high as that with modern agrotechnology, but the return to farmers' labor and investments should be higher, and the yield should be more stable. These boundary conditions suggest that the desired technology can use more of the climatic resources of the humid tropics.

Agrometeorological guidelines for agrotechnology development

The following guidelines are proposed to re-orient agricultural research and extension in the humid tropics.

First, farming operations should be based on availability of solar radiation, rather than of rainwater, in order to increase crop productivity. It is more expensive to control sunshine than to provide irrigation. Also, crop production problems in the humid tropics are fewer during the dry season.

Second, runoff should be impounded on the farms to minimize flood damage and provide irrigation water.

Third, to increase water use efficiency, more irrigation water should be lost by transpiration from plants than by percolation, seepage, and evaporation from the soil or from free standing water.

Fourth, more of the incoming solar radiation should be absorbed by crops through appropriate plant population densities and multiple cropping.

Agricultural technology that satisfies the preceding guidelines may be called *climate-based agrotechnology*, or CLIMAT for short.

CLIMAT: development and adoption

CLIMAT is a progressive program to harness climate for increasing and stabilizing crop yields. It starts with agroclimatic zonation through which climatic constraints are identified and farming activities are correspondingly adjusted. The present cropping systems research is largely at this early stage. The next stage is a deliberate attempt to modify and control the microclimate to improve crop production. It includes the sunshine-based cropping and the weather-based crop protection systems.

Agroclimatic zonation. Agroclimatic zonation should be a starting point for developing techniques for maximizing the positive aspects of climate and for minimizing the hazards. The establishment of meaningful agroclimatic zones requires knowledge of the climatic requirements of desired crops and the quantitative description of the climate of the growing areas. FAO (1978) uses rainfall, solar radiation, and other elements for classifying land suitability. IRRI (1974) largely considers rainfall in its agroclimatic classification scheme for rice-growing areas in Southeast Asia. The general environmental requirements of rice have been summarized by Robertson (1975) and Yoshida (1978).

Further improvements may be made to the classification by systematically collecting and analyzing the varietal response to weather, and determining and utilizing the probabilities of the occurrence of various climatic elements.

Sunshine-based cropping system. Water, solar radiation, and carbon dioxide must be present at optimum levels at the same time for photosynthesis to proceed at a high rate. In practical terms, this means expanding and intensifying dry season crop production (Table 1; Baradas 1978c). This practice is referred to here as the *sunshine-based cropping system.*

The major problem in the dry season is water availability. Since the conventional solution is to provide irrigation water from dams and rivers or to pump out groundwater, only a portion of the total arable land in the humid tropics is irrigable. In fact, less than half of the total arable land in the region is presently irrigated. In South and Southeast Asia, only 26.8 million of 83.4 million hectares of rice land were irrigated in 1973-75. In the dry season, only 6.6 million hectares were irrigated (Barker 1979).

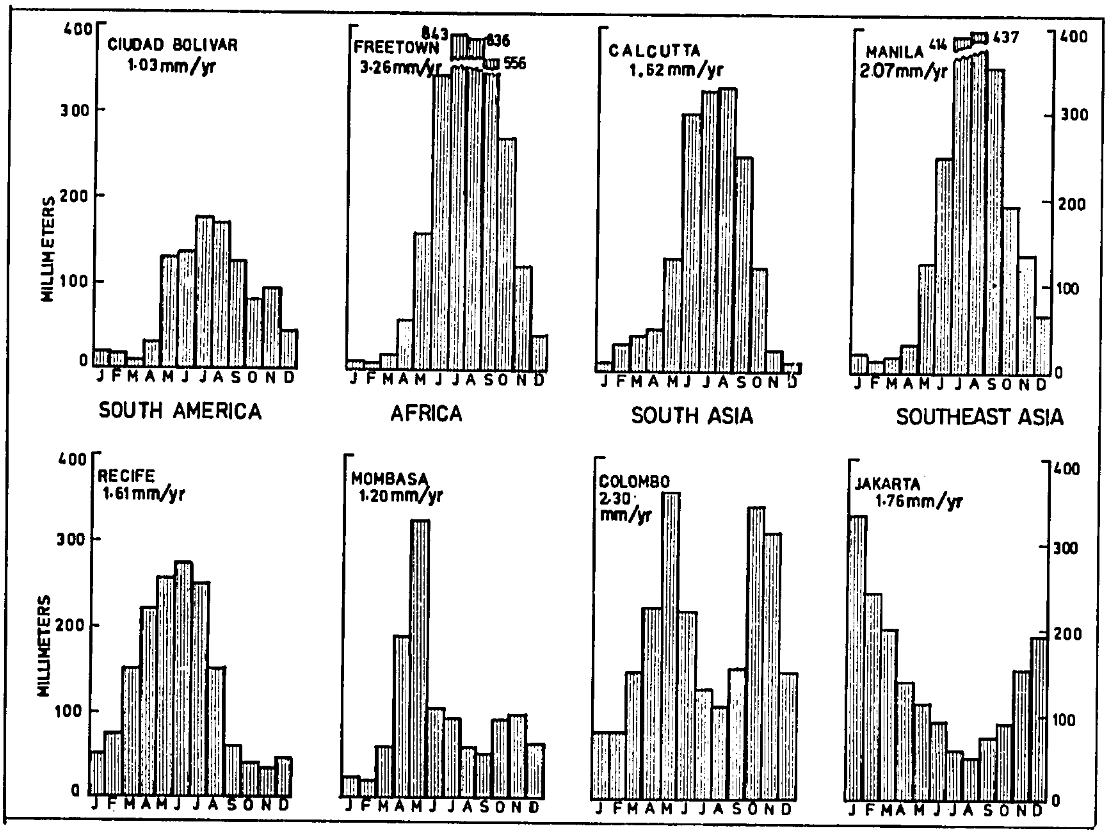
In the humid tropics, rainfall ranges from 1 to more than 3 m/yr depending on the locality. Although this is more than enough rain to support crop production throughout the year, most falls only during a few months (Fig. 1) in the greater area of the

Table 1. Status of climatic inputs to photosynthesis, classified according to type of cropping system in the humid tropics.

Climatic input	Input status by cropping system		
	Rainy season (rainfall-based cropping system)	Dry season	
		Present	Proposed (sunshine-based cropping system)
Solar radiation	Limiting	Sufficient	Sufficient
Water	Generally excessive, but can be limiting	Limiting	Sufficient
Carbon dioxide	Sufficient	Sufficient	Sufficient

humid tropics. Thus, there is a need to impound the rainwater on the farm.

A promising solution for small farmers is a farm pond system. Some Asian farmers already use farm ponds. Gibson (1972) lists several advantages of farm ponds: direct farmer participation, low cash inputs needed relative to the contribution in-kind paid by farm family labor, construction can be



1. Mean monthly and annual rainfall at selected stations in the humid tropics with distinct dry and wet seasons.

done by hand during idle months, little government financial support needed except credit, and negligible foreign exchange required.

There are at least five additional benefits in impounding rainwater in farm ponds (Baradas 1978b). First, losses when water is brought from distant reservoirs are reduced. Second, the ponds trap soil sediment and nutrients that normally drain to the rivers. These sediments and nutrients can be recycled on the farms in the dry season. Third, flood damage is minimized if runoff from the farms is separated from runoff from the forest and urban portions of the watershed. Fourth, fish grown in farm ponds provide additional income and food to the farmers. Fifth, the social problem in distributing water from large irrigation systems is eliminated.

Weather-based crop protection system. An effective crop protection system prevents crop losses at minimum cost. There are three general approaches to the weather aspect of crop or disease development. One approach is to forecast when weather conditions warrant appropriate control measures.

A second approach is to make the crop microclimate unfavorable to pest or disease development. For example, the plant population or crop row orientation may be designed to keep humidity below the disease development threshold.

A third approach is to time the planting so that the expected weather condition is unfavorable to pest or disease development, or to localize the pest or disease inside the cropping area. The latter condition generally exists in the dry season.

Schrödter (1975) noted that most crop disease warning services rely on reports that do not include micrometeorological observations although it is known that diseases are closely related to such observations. He also pointed out that existing methods assume that epidemics are dependent on meteorological factors alone. To correct this problem, he suggested the use of "negative forecasts," which give the length of time that unfavorable weather precludes an epidemic.

Kisimoto and Dyck (1976), reviewing studies on climate-rice pest relations, found that stem borer infestation was severe when rainfall was low and temperature high. The migration of certain insects was related to wind trajectories. They suggested that more conclusive evidence is needed to substantiate the findings.

Baseline CLIMAT validation

It has been customary to develop a technology and then find out the constraints to its adoption. Researchers have been passing the burden for adoption to the extensionists. The situation should be turned around: the extension group should specify the constraints to increased crop yields and the technology that the farmers need and will accept.

Several studies have been conducted on the available resources, attitudes, aspirations, and activities of small farmers. A baseline package of CLIMAT should be assembled immediately, improved with farmers' comments, and validated in farmers' fields at representative sites in the humid tropics. Unlike previous field trials in which *farmer-participants* passively implement the technology, CLIMAT *should* encourage them to *criticize and suggest improvements on the new technology from their point of view.* The technology so generated would have a much higher and faster adoption rate.

CONCLUSION

Inadequate water control on the farm, low sunshine, and other difficulties during the rainy season are major constraints to high and stable yields of rice and other crops in the humid tropics. The direct solution of these constraints would have faster and greater impact on food supply than developing drought-resistant varieties, new agroclimatic classifications, and sophisticated models of water balance, rainfed cropping systems, and crop-weather relations.

Collection of rainfall in suitable farm ponds will minimize flood damage during the rainy season and provide irrigation water, especially in areas with no economical surface water or groundwater source.

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Climatic factors in rice-based cropping systems research

H. G. Zandstra, J. F. Angus, and M. M. Tamisin

This paper describes the cropping systems research methods used by IRRI, the importance of climatic analysis for each research phase, and the growing season for rice-based cropping systems. The paper explores several approaches that efficiently use climatic information for predicting land suitability for different cropping patterns and for a complete evaluation of the performance of alternative patterns over time. Some approaches lead to climatic classifications which can be represented on maps or as base data. Others may lead to analytical or simulation methods to evaluate crop performance or crop-related events at a specific location. Although our research on climatic factors and cropping systems is far from complete, we indicate certain research priorities.

The possibility of introducing additional crops in a crop production system is difficult to predict or measure confidently based on 2 or 3 years of experimental cropping pattern trials because in most locations, rainfall patterns vary widely from year to year. For this reason, we studied ways by which historical weather records can be used to evaluate the feasibility of crop intensification and help interpret the results of cropping pattern trials.

CROPPING SYSTEMS RESEARCH

Cropping systems research developed by IRRI in collaboration with the Asian Cropping Systems Network consists of five phases. Research activities and specific methods have been developed for each phase through the Cropping Systems Working Group (Cropping Systems Working Group Reports, 1975-78). The following briefly describes the role of climatic factors and the analysis for each phase.

Target area selection

One or more geographic areas representative of large homogenous production zones are selected. The areas should have potential for increased production and cropping intensity, a good marketing system, adequate infrastructure, and extension services.

The selection of acceptable production zones depends on the ability to interpret the climate in relation to cropping pattern performance. Climatic classifications allow better estimates of the potential for productivity increases and the area to which results can be extrapolated.

Site description

Existing cropping patterns, the physical and socioeconomic environments, and constraints to production are described. The farm environment determines priorities for research at the site and at supporting research stations. Improved analysis of the effects of climate on cropping pattern performance can help simplify the site description phase by allowing researchers to concentrate on the physical parameters that really matter.

Cropping pattern design

Alternative cropping patterns that are well-adapted to the area are designed, taking into consideration the area's physical and socioeconomic characteristics, the performance of existing cropping patterns, and the availability of management technologies for those crops included in the patterns.

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The design for biologically feasible cropping patterns is a process that matches the crops' physical requirements (over their growth duration) to the area's physical conditions (over the year). Panabokke (1974) provide an outstanding example of such matching for crop water requirements in Sri Lanka's dry zone. Improved climatic analysis and climatic classifications result in cropping patterns with a higher probability of success. Increased efficiency reduces the time and cost associated with experimental field trials.

Testing of cropping patterns

The assumptions about agronomic feasibility made at the design stage are now tested by using the patterns in farmers' fields. Climatic factors must be measured during this phase to allow a precise interpretation of the cropping patterns' performance, and the extrapolation of testing results over time by the use of historical records. Improved methods of collecting and analyzing pertinent climatic data are required. There is a lack of information about the parameters to be derived from the measured data that can be readily associated with the performance of cropping patterns.

Crop performance or specific cropping event simulations can aid in identifying the data to be collected and the analysis that will strengthen the interpretation of field tests. Simulations of dry-seeded rice emergence and the performance of a second rainfed rice crop are now used in IRRI's cropping systems program.

Preproduction testing

The most desirable patterns identified during the testing phase should be evaluated at a number of sites that possess the same physical characteristics as those for which the patterns were designed. The identification of extrapolation areas requires that quantitative methods allow the identification of homogenous climatic regions from climatic data that is inadequate for large geographic areas. Substantial methodology development is required for this purpose (Morris and Rumbaoa 1979).

RICE-BASED CROPPING SYSTEMS

Rice-based cropping systems differentiate in three major groups: dryland, rainfed wetland, and irrigated wetland. Dryland rice culture does not accumulate water on the field surface. It utilizes land that, except for limited periods, does not hold moisture in the rooting zone in excess of field capacity. Wetland rice culture encourages water accumulation on the soil. It utilizes land that keeps the rooting zone saturated for a substantial part of the rice growing season. Rainfed wetland and irrigated wetland are similar, particularly where irrigation is not used throughout the year.

Crop intensification in dryland rice-based systems allows complex sequential, relay, or intercropping patterns. In typical wetland rice fields, intensification usually involves the addition of crops to the crop sequence. Crop intensification is made possible by the following mechanisms:

1. Early-maturing varieties allow farmers to capture as much as 45 days of the growing season for additional crop production.

2. Early wetland rice crop establishment by seeding on puddled soil generally allows farmers to harvest 2 weeks earlier than if they transplant the first rice crops. Seeding rice in dry soil allows a gain of 3 to 4 weeks.

3. Tillage methods allow a reduction of turnaround times from 30 days to 10 days between crops without reducing yields. Ratoon cropping may further reduce turnaround time and the cost of land preparation and planting.

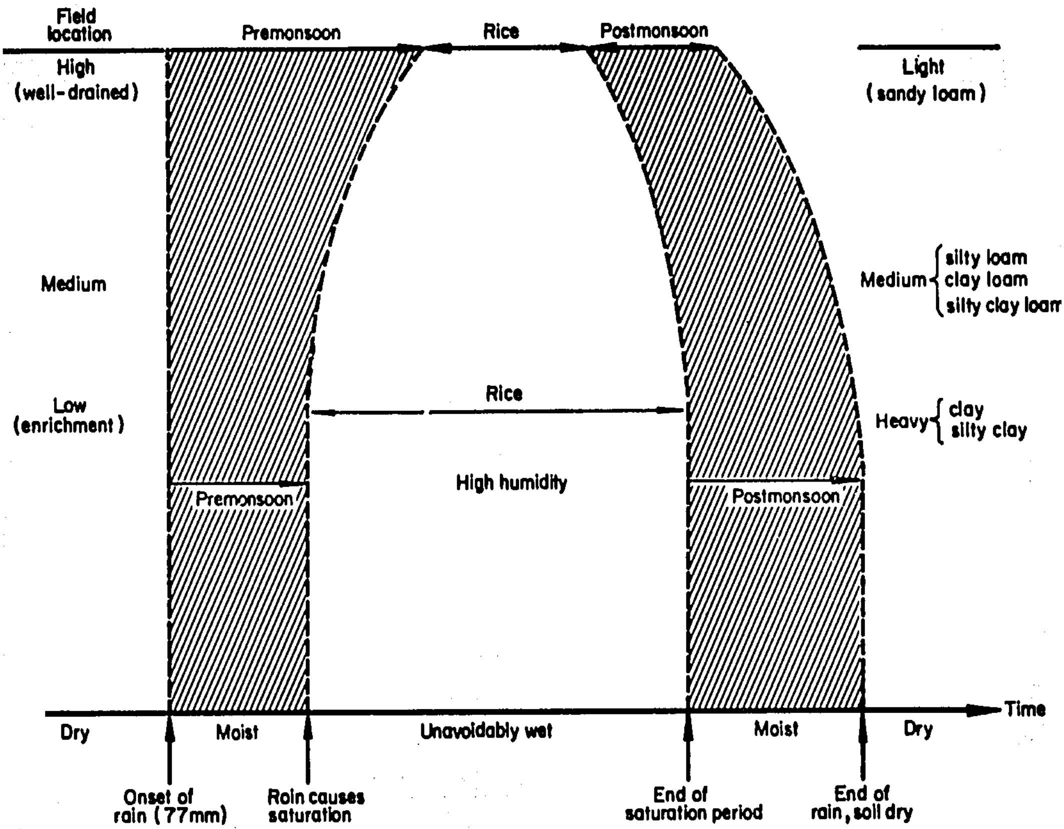
4. The use of older rice seedlings (up to 35-40 days) can reduce the field duration of rice to only 75 days.

5. Residual soil moisture held in the profile after wetland rice culture is often sufficient to produce a short-duration well-rooted upland crop, if care is taken to reduce water loss from the soil surface in early growth phases.

6. Intercropping and relay cropping are effective tools to increase dryland productivity by structuring canopies that are more efficient than those of sequential sole crops throughout the growing season.

The cropping pattern suited for a location depends on the prevailing climate and land characteristics. The rainfed growing season can be divided into four parts (Fig. 1):

1. The dry season. Duration can vary from 0-6 months and soil water



1. The growing season components of wetland rice-based cropping systems.

contribution to crop growth approaches zero.

2. The premonsoon moist period. Because rice will generally germinate, emerge, and sustain growth after accumulated rainfall exceeds 75 mm, we have identified that as the start of this period. The periods ends when the topsoil becomes saturated and upland-crop growth is affected by lack of oxygen in the root zone. The duration of the period depends on the following:

a. The rate of onset of the monsoon. In the Philippines, this varies from 37 to 118 days with an average of 69 days. Five sites had an onset duration greater than 90 days.

b. Soil texture. Heavy-textured soil profiles will reach saturation more readily because of reduced percolation rates. For similar rainfall regimes, the premonsoon period will be shorter for the heavy-textured soils than for light-textured soils (Fig. 1).

c. Field location in the landscape. Lateral water movement greatly changes water availability to wetland rice fields. High-lying fields will lose water readily and receive water only from rains, whereas low-lying fields receive much water from higher-lying fields and dispose of less water through drainage. High-lying fields have a greater potential for long premonsoon moist periods than low-lying fields.

3. The wet period. In wetland fields, this is characterized by saturation of the top soil or long periods of standing water. It ends when the soil profile drains. Only rice can be grown during the wet period.

In dryland conditions, rainfall frequently exceeds the ability of the soil to dispose of water through percolation. Several periods of 4 to 10 days can occur in which the root zone holds water well above field capacity. This leads to yield losses for upland crops[1], and losses in

[1] The term upland crops is preferred to the (strictly correct) term dryland crops, to avoid confusion with crops particularly suited to arid conditions.

nitrogen efficiency for upland crops and dryland rice. Losses due to excessive moisture are most common in the clays and clay loams of Alfisols or Inceptisols, less common in Ultisols of similar texture, and least common in Oxisols. Where the frequency of root zone saturation becomes too great, farmers generally modify the land. By surrounding the fields with bunds and puddling the topsoil, they increase effective rainfall, decrease water loss, and create wetland fields. During the wet period rainfall and humidity are too high to produce crops susceptible to seed spoilage. Dryland rice and, in the better-drained soil types, corn and cassava are suitable field crops.

Generally, the number of months with rainfall exceeding 200 mm provides a rough indication of the length of the wet period (Oldeman and Syarifuddin 1977). The end of the wet period comes earlier for high-lying or light textured soils than for low-lying, heavy-textured soils (Fig. 1).

4. Postmonsoon periods. Moisture content in the root zone is reduced from above-field capacity to the point where all extractable water has been used by crops. The duration of this period greatly influences the possibility for upland crop production after rice. In areas where rains stop abruptly (no months with rain between 75 and 150 mm), the crops depend on water stored in the profile or on that provided by a shallow water table. In these areas, loams, silty loams, and very fine sandy loams have greater production potential than heavy-textured soils because of the increased groundwater contribution. The rate of basin groundwater and even perched groundwater at the end of the rainy season is not substantially conditioned by profile texture. In such a case, the medium-textured silty soils will receive greater ground-water support than heavy clays for postmonsoon upland crops. These light-textured fields with good potential for surface drainage can be managed so that topsoil moisture levels remain well below saturation toward the end of the wet season.

Irrigated wetland systems

Irrigation from river diversions is generally limited to extending the wet period and the postmonsoon moist period because water is normally not available during the premonsoon moist period. Irrigation from reservoirs or wells is more flexible and can greatly lengthen the growing season and the potential for premonsoon and postmonsoon crops. In most rice-growing areas the "unavoidably wet period" can be reduced only by major land modification -- drainage, poldering, ditch, and dike systems. Without such modifications land use during the wet monsoon period is virtually limited to rice production which can be improved by irrigation.

ANALYSES OF CLIMATIC FACTORS FOR RICE-BASED CROPPING SYSTEMS

Rainfall, temperature, flooding, and wind events combine to create a large number of growing season characteristics. Land modifications through leveling and bunding, and provision of drainage or irrigation further diversify the effects of weather. The resulting variability in growing conditions is reflected in the wide variation in cropping patterns practiced by farmers throughout Asia (Dalrymple 1971, ICAR 1972).

Climatic analyses contribute to cropping systems research by identifying the parameters of particular relevance to crop adaptation and productivity that affect important crop events such as land preparation, crop establishment, pest control, and postharvest processing; and by providing data for the partial or complete simulation of crop growth and production or for specific crop production events.

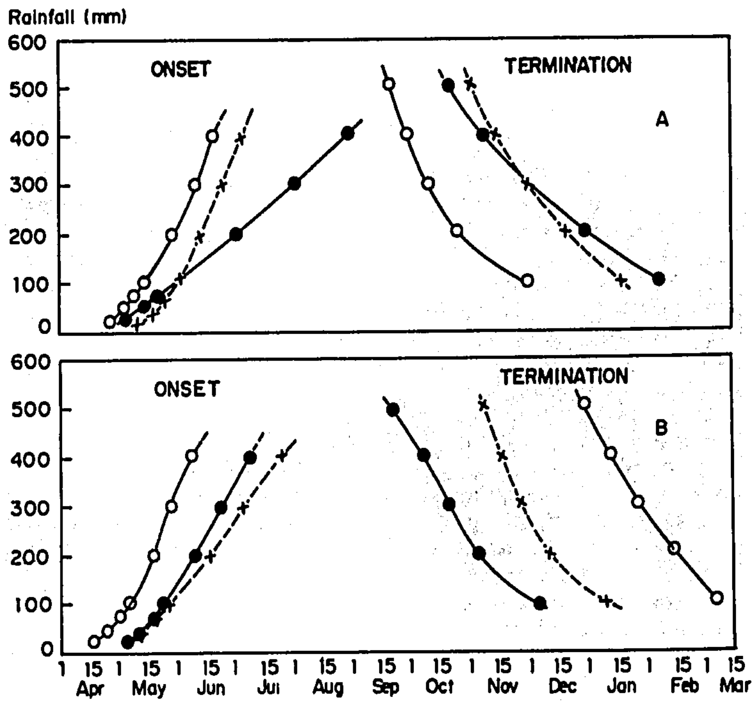
Identification of climate parameters and the description of land

The collection and ready access to climatic data are essential. An example of standard climate files is the Integrated Climate Data file developed by IRRI in cooperation with the Philippine Atmospheric, Geophysical, and Astronomical Service Administration (PAGASA)(Angus and Manalo 1979). This file of weekly climatic data for 47 Philippine weather stations, now contains weekly rainfall totals for 20 or more years. It provides weekly means at each station for rainfall, class A pan evaporation, solar radiation, maximum screen temperature, minimum screen temperature, dry bulb screen temperature (0800 h), wet bulb screen temperature (0800 h), humidity, and phyto-day length. Where necessary, solar radiation is estimated from the duration of bright sunshine or from records of observed cloudiness (Tamisin 1977). The radiation records are used along with measurements of wind run and vapor pressure deficit to calculate evaporation using the "Modified Penman" approach (Tamisin et al 1979).

Greater accessibility to climate files is important to cropping systems researchers and planners to provide information for the selection of research and production program sites. Climate files also help identify homoclimes to which research results can be extrapolated.

The collection of climate data from several sources is followed by quality control, completion of data sets by estimation of missing components, identification of boundaries for classification, and finally presentation of results in maps or tables. Climatic classification is generally concerned with rainfall, evaporation, temperature, solar radiation, and crop damage conditions caused by frost, hail, high winds, and floods. Each factor or combination of factors can be characterized by different parameters. A useful classification of rainfall types has been developed (IRRI 1974, Oldeman and Suardi 1977) based on the typical monthly crop water requirements of 100 mm rain for upland crop production and 200 mm for wetland rice production. This classification provides general information about the average duration (in months) of rain sufficient to maintain crops on a large scale. It has been used to prepare rainfall maps for Java (Oldeman 1975), Sulawesi (Oldeman and Syarifuddin 1977), and Sumatra in Indonesia, and the Philippines, Bangladesh, and Thailand (by E.B. Manalo at IRRI).

Other rainfall analyses involve measuring the amounts of rainfall received on certain dates (Fig. 2), the duration of the growing season or such time-related aspects as the onset and termination of rains for different parameters (Table 1), or the time during which pronounced midseason droughts occur (see Slatyer 1960 and Nicholls et al 1967 for useful examples). To be of most use for crop scheduling decisions, these classifications must consider certain levels



2. The rainfall accumulated after 1 April (onset) and the rainfall still to occur before 1 April (termination) for different dates of the onset and termination of rains at Iloilo (x-x), Dagupan (0-0), and Zamboanga (●-●) for Figure A and at Tuguegarao (x-x), Malaybalay (0-0), and Cabanatuan (●-●) for Figure B. ($P = 0.70$)

Table 1. Growing season rainfall characteristics for selected sites in the Philippines.

Site	Onset			End			Length	
	Date[a]	Rate[b]	Sd[c]	Date[d]	Rate[e]	Sd[f]	Days[g]	Sd[h]
Iba, Zambales	14 May	26	11	5 Nov	45	22	175	27
Daet, Camarines Norte	23 Apr	60	25	7 Mar	46	19	318	24
Tigbauan, Iloilo	15 May	41	17	3 Jan	75	29	233	31
Aparri, Cagayan	18 May	61	24	9 Feb	77	25	267	32
Laoag, Ilocos Norte	24 May	31	16	19 Oct	45	29	148	31
Dagupan, Pangasinan	3 May	42	11	9 Nov	58	21	190	38
Ambulong, Batangas	12 May	51	15	10 Dec	67	23	212	28
Baler, Quezon	13 Apr	39	15	11 Mar	67	21	332	16
Tuguegarao, Cagayan	11 May	63	21	26 Dec	67	23	229	37
Bayombong, Nueva Vizcaya	9 May	56	31	10 Jan	89	30	246	48
Bontoc	18 May	36	47	13 Nov	64	63	179	58

[a]Accumulated rainfall Ra = 75 mm at P = 0.50. [b]Days between Ra = 75 and Ra = 400 at P = 0.50. [c]Standard deviation of day on which Ra = 200 (days). [d]Remaining rainfall (R_r) = 100 at P = 0.50. [e]Days between R_r = 500 and R_r = 100 at P = 0.50; [f]Standard deviation of day on which R_r = 200 (days). [g]End date - onset date. [h]Standard deviation of length of growing season.

of probability. The maps of onset and duration of rainfall at $P = 0.70$ (Fig. 3, 4) provide examples.

These graphs and maps are derived from rainfall records from 55 locations with record lengths of 40 or more years.[2] For the start of the rains we used the probability of the site having received a certain total amount of rain on a given date. For the end of the rains we used the probability of the site still receiving a certain amount of rain after a given date. For each year several rainfall accumulation criteria were used for onset: 25, 50, 75, 100, 200, 300, and 400 mm, and for termination: 500, 400, 300, 200, and 100. To use onset and termination dates for crop scheduling, there should be no relationship between the date of onset and termination within a given year. Our analyses of 55 stations showed that a significant correlation of the 75 mm onset date with the 100 mm termination date occurred only in 5 sites. For these sites R^2 ranged from 0.31 to 0.54. For 31 locations the R^2 was less than 0.15 and for 19 locations, between 0.15 and 0.30.

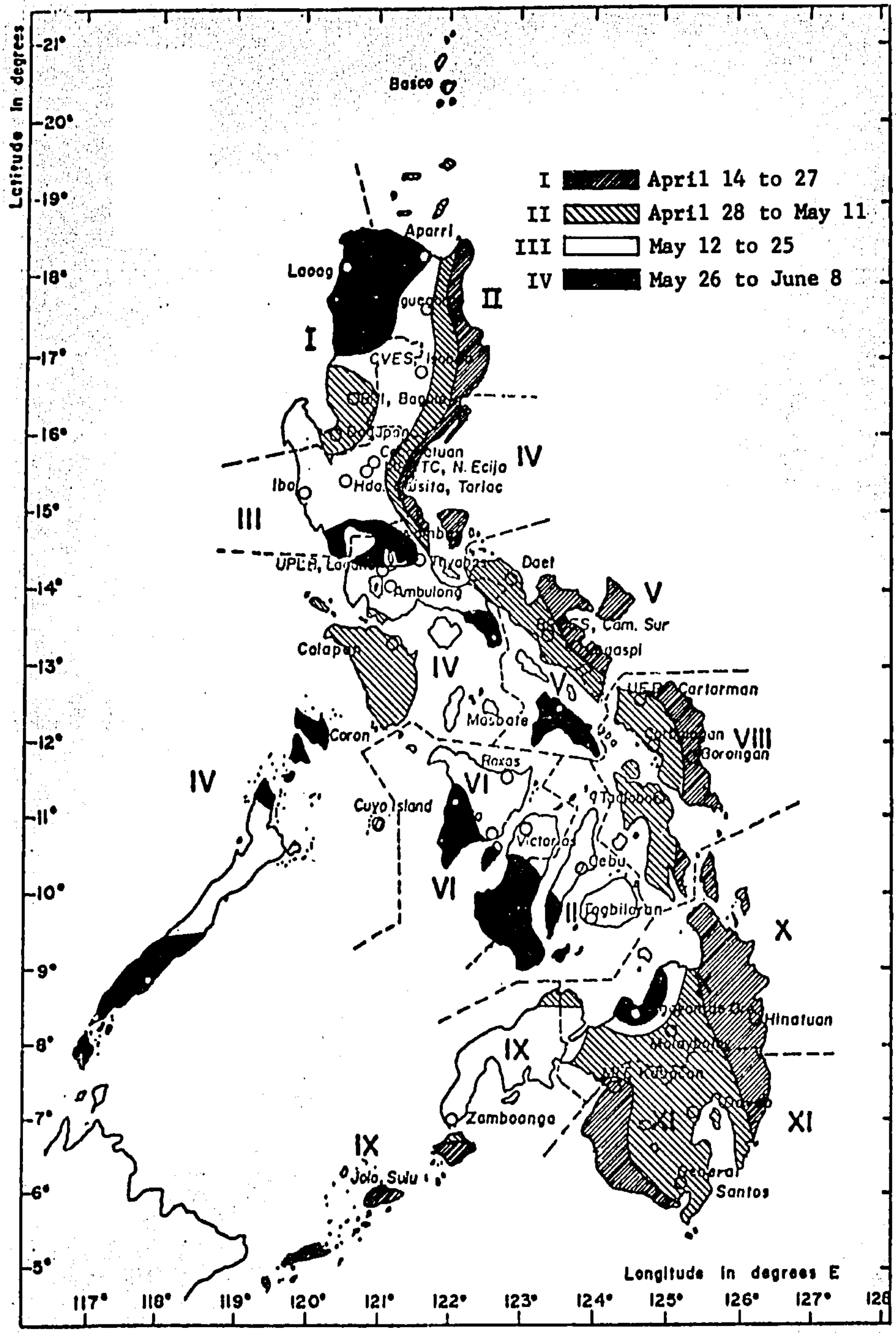
[2]Assistance for access to these given by Dr. W. David, Institute of Agricultural Engineering and Technology, University of the Philippines at Los Baños, is gratefully acknowledged.

Year-to-year variability is much less pronounced for evaporation and solar radiation than for rainfall, and their effect on crop production can generally be captured with sufficient accuracy using monthly or weekly averages. After data collection or data generation (Tamisin et al 1969), evaporation and solar radiation values can be readily mapped to provide an image of the spatial distribution of differences in their values, as demonstrated in Figure 5.

For climatic characteristics such as storms (typhoons), hail, frost, and floods, it is important to provide classifications of the probability of their occurrence at different intensity levels during critical parts of the growing season. Kintanar (1973) and Subbaramayya (1971) provide examples on cyclone probabilities.

Combinations of climatic factors, such as atmospheric water balance or the soil water balance (Thornthwaite 1948), provide added insight into their effect on crop production potentials.

For example, a more direct analysis of the four growing season components and the dates of their onset and termination employs a field water balance for rainfed wetland rice. In the humid tropics, lateral depletion and enrichment through overflow, seepage (surface) and percolation (subsoil) can substantially modify the duration of the growing season components for different rice

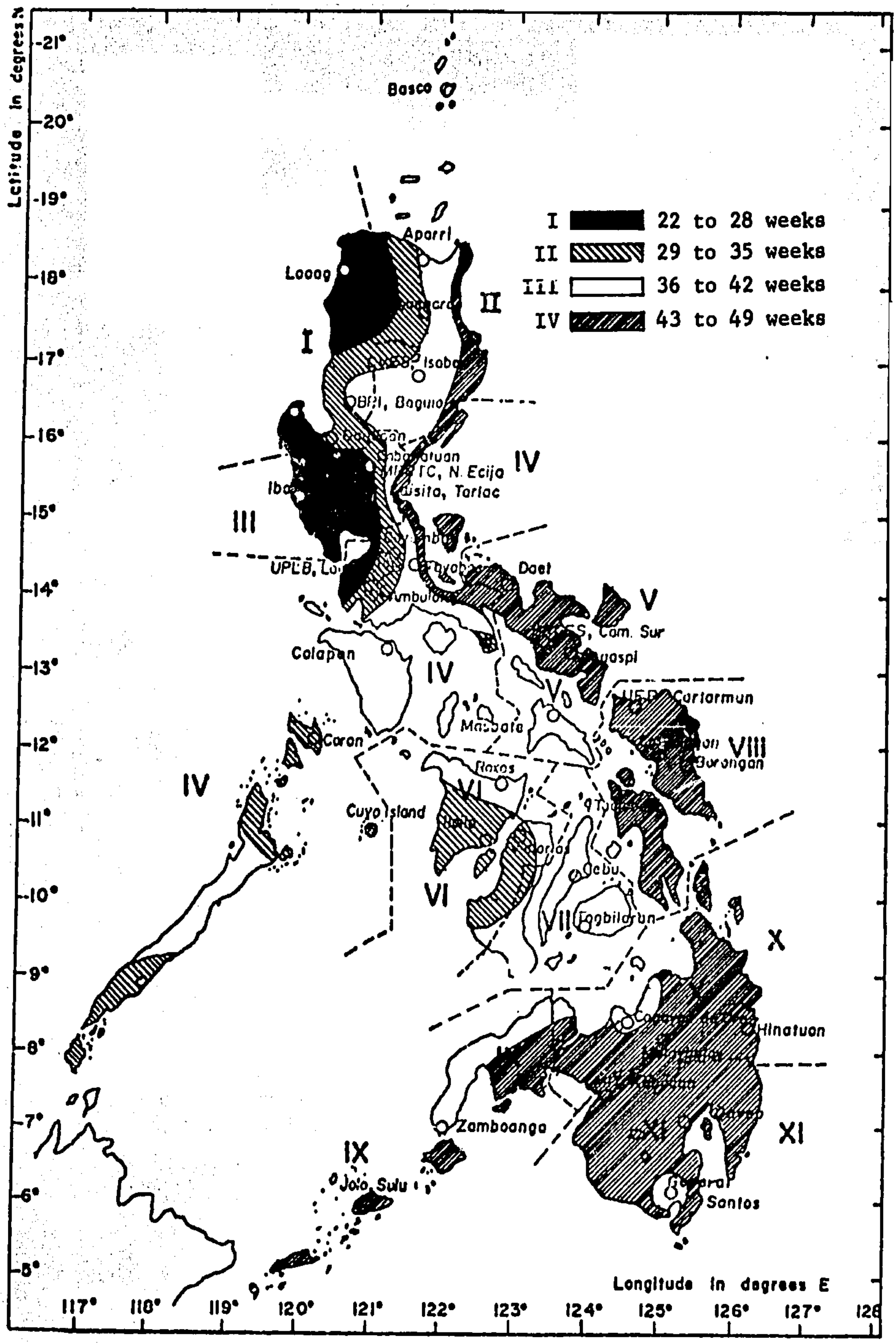


3. Dates of onset of the growing season on which accumulated rainfall after April exceeds 75 mm at $P = 0.70$.

fields (Morris and Zandstra 1979).

We developed a wetland field water balance model, which captures most of the effects of landscape position and soil textural differences between fields by varying assured seepage and percolation rates.

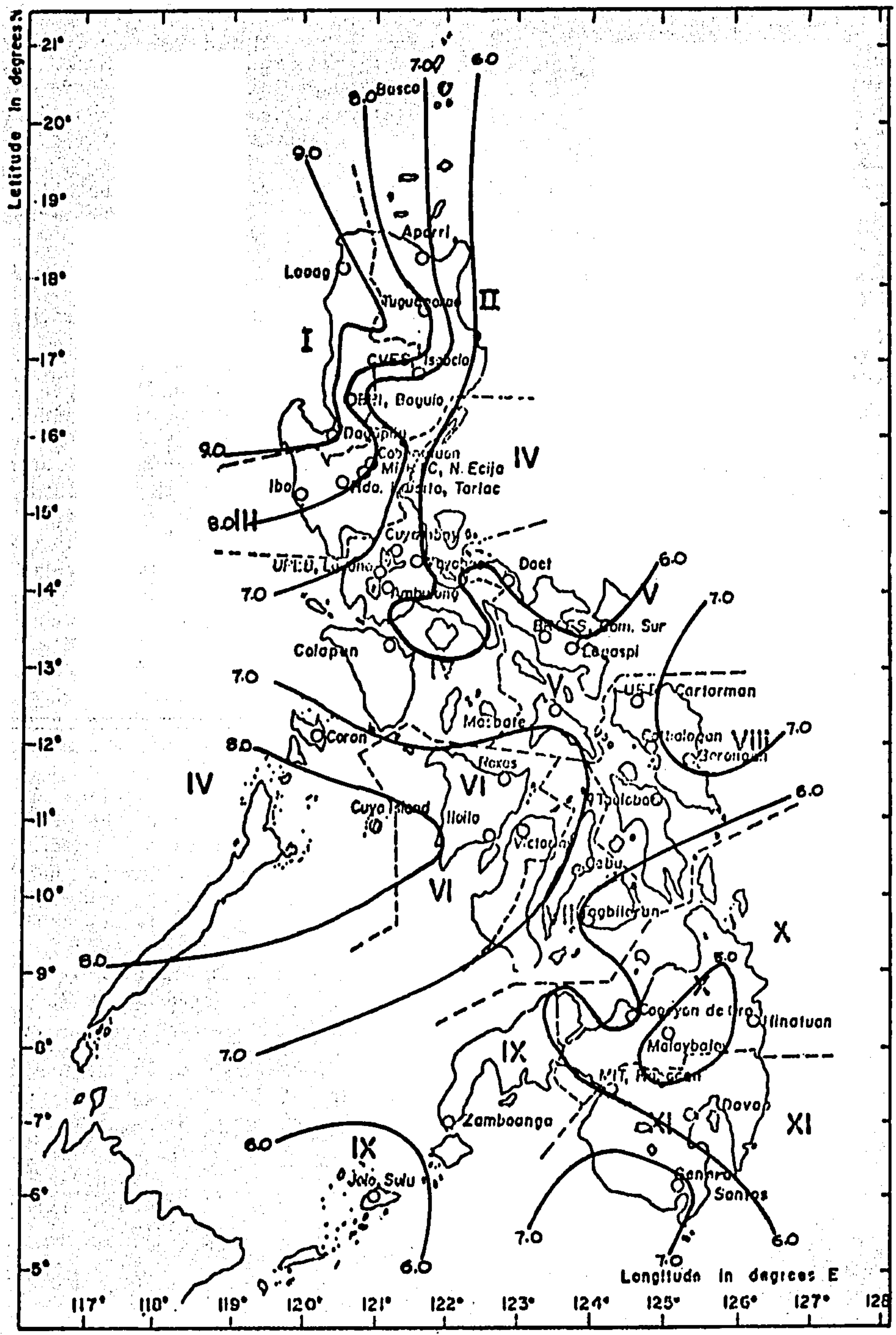
Results of soil water simulation are now used to classify the growing season into four components and evaluate their



4. Duration of growing season between the dates on which accumulated rainfall exceeds 75 mm and on which 100 mm rain is still to fall at $P = 0.70$.

onset and termination in a probabilistic manner similar to that presented for rainfall in Figure 2.

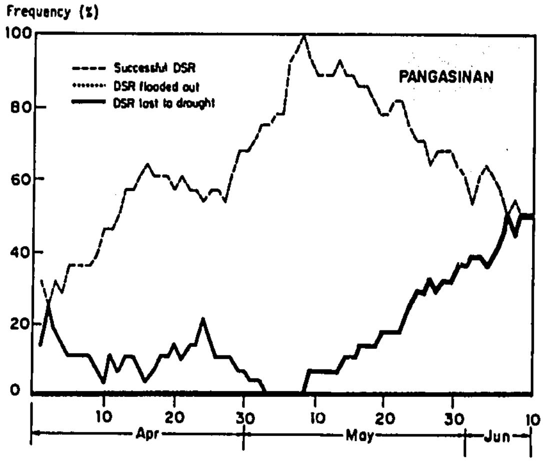
Linking of the water balance with spatially distributed soil data is probably best done by running the model with different soil parameters and relating these to observed field characteristics. A major weakness of this procedure lies in our limited ability to classify fields in terms of their tendency to collect and retain water



5. Distribution of mean daily evaporation (mm) for April in the Philippines.

(hydromorphicity). In addition, where the basin groundwater level rises above the surface during periods of the year as a result of river basin floods, most assumptions of typical field water balance models are swept away.

Other combinations of climatic variables merit consideration for classification and mapping. A water stress index (evapotranspiration of a standard full canopy/potential evapotranspiration) derived from a water balance output will



6. Frequency of success, loss to drought, and loss to flooding of dry-seeded rice (DSR) for seeding dates from April to 9 June in Pangasinan, Philippines, based on simulation of DSR germination, emergence, and early survival over 28 years.

capture major moisture-related differences in the production potential of regions and growing-season periods (Nix 1976). Nix also suggests the use of photothermal quotient to represent the light energy available for photosynthesis per unit of developmental time.

Simulation of specific cropping patterns

Simulation methods are useful in evaluating the effects of climatic conditions on specific cropping events. They help researchers answer questions about the performance of new technology and evaluate how year-to-year variations in weather affect the long-term stability of results. Simulation methods can help identify the type of weather parameters to be classified and the class boundaries that make clasifications relevant to crop performance.

Of specific interest to rice-based cropping systems are simulations that determine the most appropriate seeding dates or methods, effects of short-duration floods on upland crop performance, crop damage through typhoons or low or high temperatures, loss of upland crop quality due to high rainfall and humidity, effects of early water stress on dry-seeded rice crops and on the second transplanted rice crop, soil water movement to upland crop roots, and the effects of water loss on root growth in soils with high mechanical impedance.

More information is also required on the effect of weather characteristics or derived environmental factors on crop production aspects such as germination, emergence, phasic development, the number of flowers initiated, tuber formation, sterility, senescence, carbohydrate levels in plant parts at harvest time, and product quality.

Because of the important effect timeliness has on farm operations, more studies are required to evaluate relationships between weather and the timing and effectiveness of premonsoon and postmonsoon primary land preparation, secondary land preparation for dry and wetland culture, weeding, harvesting, and postharvest processes such as grain drying. Such studies would be useful in identifying climatic parameters to be used in large-scale climatic classifications and mapping, and in the simulation of specific events.

An example of a simulation model used for specific events are studies on dry-seeded rice conducted in IRRI's cropping systems program. The evaluation of dry-seeded rice success or failure over 28 years for seeding dates from 1 April to 9 June indicates that the most successful seeding dates are 7 to 15 May in Dagupan, Pangasinan, Philippines (Fig. 6).

Results of such simulations can also be used to compare the usefulness of moisture and rainfall conditioned decision-making strategies. Conditioning the seeding decision to soil moisture or accumulated rainfall events achieved 80% (or greater) success rates 7 to 10 days earlier than a simple time-based decision for Dagupan (Table 2).

Table 2. Decision-making strategies for the date of dry-seeding rice.

DSR strategy	Dagupan (28 years): 1st occurrence each year: Success (%)	Dagupan (28 years): 1st occurrence each year: Date	Dagupan (28 years): % not occurring[a]
Top 5 cm of soil moist (≥15 mm)	68	28 Apr	0
Top 30 cm of soil moist (≥90 mm, ≤135 mm)	85	29 Apr	0
Accumulated rain (≥90 mm)	96	3 May	0
Top 30 cm of soil moist and last day's rain (≥10 mm)	89	27 Apr	0

[a] Before 9 June.

imulation of cropping systems

. cropping system comprises all components equired to produce a set of crops and ncludes all necessary physical and biolo-ical factors, technology, labor, and anagement. Simulation of cropping system emands whole-farm coverage and even with implification, leads to great complexity n resource allocation and transfers. limatologists and crop scientists are robably more concerned with simulating nd understanding events associated with specific cropping pattern. A single ropping pattern can be identified for very plot the farmer owns, by the spatial nd temporal combination of crops on that lot, and the management used to produce hem. Each component crop (including ntercrops) needs to be simulated to imulate a complete cropping pattern.

The modeling of the agronomic erformance of multiple cropping systems s at this time little more than a esearch tool. It can, however, provide nformation on the feasibility of complet-ng a crop sequence given certain growing-eason characteristics and assumptions bout time and water requirements of land reparation and other operations (Angus 1979). Such simulation models can also estimate the potential productivity of component crops as derived from moisture availability, temperature regime, day length, and solar radiation (Nix 1976). Actual performance of the cropping pattern in a given land type is, how-ever, difficult to predict. Major effects of intermittent drainage, adverse soil, chemical or physical factors (soil strength, textural dis-continuities, etc.), timing and methods of input application, weeds, insect and disease pests, short periods of sub-mergence of rice, temporary flooding of upland crops, and loss of crop quality are more difficult to capture.

Until individual studies of these specific crop events have been conducted and expressed in specific process simu-lations, modeling of multiple cropping patterns requires a familiarity with the pattern in farmers' fields. This demands repeated testing of the cropping sequence involved and the interpretation of testing results with the aid of cli-matic records obtained at the test location. Cropping pattern simulations based on such field tests can then provide added insight into the effects of major yield-limiting factors.

CONCLUSION

The identification of improved cropping patterns and the associated increase of cropping intensity requires careful con-sideration of climatic factors that prevail in a region. The relationship between agronomic performance of cropping patterns and climate is complex and interacts with other components of the environment, particularly those related to the soil and land topography. A more extensive utilization and interpretation of climate data will support agricultural research in its task to fit production systems to different environments.

Cropping systems researchers use climate data for the description of the production environment in different regions (including the stochastic compo-nents) and for the simulation of specific cropping events, crops or cropping patterns. This provides a basis for the establishment of research priorities and reinforces experimental observations about new technologies with results from simulations over longer periods of time or under dif-ferent weather conditions.

Both activities require access to long-term climate records at a great number of observation points. National and international institutions should give high priority to gathering, evaluating, standardizing, and providing historial climatic records.

Priority should also be given to identifying climate parameters that are of particular relevance to crop scheduling and crop production. That requires improvement in the monitoring of climate associated with field experi-ments. The FAO expert consultation on Soil-Crop-Weather relationships held at Canberra in May 1977 addressed the issue of necessary and minimum data collection for field experimentation, but its results have not received the exposure they deserve. In addition to collecting weather measurements with their expe-riments, researchers must be more encouraged to associate year-to-year, season-to-season, and site-to-site variations in research results with variations in weather conditions.

Simulation models of cropping events help develop quantitative methods to relate weather to crop productivity and explain variations in research results. These models depend greatly, however, on research conducted in support of process simulation.

Research on soil-crop-weather and management-weather interactions should receive greater attention than it has in the past.

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IV. Climatic change and variability

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The impact of world weather change on rice production

J. W. Stansel

The world's rice areas were classified according to climatic constraints on production and by rice culture systems (based on water use). This provided a sensitivity analysis of the impact of climatic change on world rice production. Ranges of possible climatic changes used in this study were ± 2°C, ± 15% precipitation, and ± 8% solar radiation.

Temperature change modifies growing season constraints and influences the rate of plant development. A 1°C change in mean temperature could result in a change of 17 to 25 days in effective growing season. Precipitation changes would have a differential impact on each rice culture system. Interactions between temperature and precipitation could be expected. In areas of high yielding irrigated rice, precipitation changes were assumed to influence yields through changes in solar radiation levels.

It was estimated that world rice production could be decreased 19% by the combination of a 2°C temperature reduction and a 15% precipitation reduction. Increases in these climatic variables could increase world rice production by a similar magnitude. Modest changes of 0.5°C and 10% precipitation could alter world rice production by ± 10%. By developing cold tolerant rice cultivars with increased photosynthetic efficiency, the estimated yield depressions caused by climatic change could be overcome.

The announcement by United States Transportation Secretary William F. Coleman, Jr. that the United States would allow the controversial French supersonic jet (SST) to land in Washington, D.C., and in New York City for a 16-month trial period drew varied reactions. There was concern that pollutants from the SST flights might damage the ozone layer and result in climatic change. In response, the Department initiated its Climatic Impact Assessment Program (CIAP) to evaluate existing scientific data, to organize new research programs, and to prepare a full analysis of the impact of climatic change on the world. A major consideration was food production and an evaluation of climatic change on world and U.S. rice production was made.

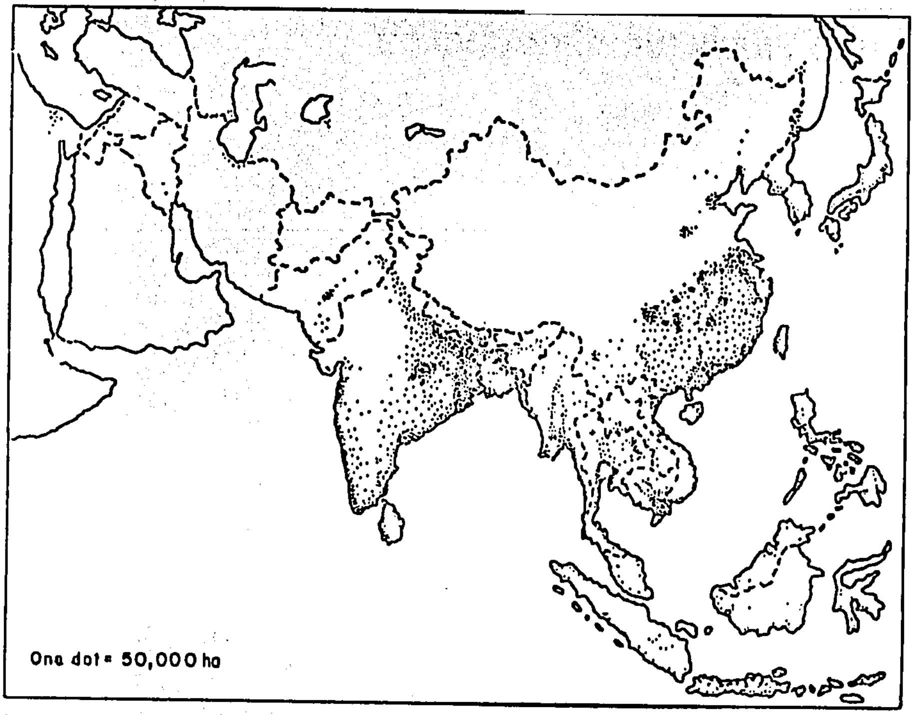
The world's climate seems to be changing, but scientists disagree on how and to what magnitude. Some areas such as Africa experience severe droughts, while others are flooded at unprecedented rates. Some regions experience cooler temperatures, while others have warmer temperatures. True climatic differences, if they occur, are being masked by factors, which may be only normal climatic shifts.

This paper is a Climatic Impact Assessment Program (CIAP) report on possible impacts of climatic change on world and U.S. rice production. It does not predict climate changes, but gives a rough estimate of what such change can mean to world and U.S. rice production.

CLIMATIC RANGE OF RICE PRODUCTION

Rice producing areas in Asia are shown in Figure 1. Rice is grown in northern China at latitude 50°N, in central Sumatra on the equator, in Australia at 35°S latitude, and at all latitudes in between. Rice is planted at all elevations -- from sea level in Brazil to 3,000 m in Nepal. It grows at Akyab, Burma, with more than 4,500 mm rainfall,

Texas Agricultural Experiment Station, Texas A&M University System, Beaumont Agricultural Research and Extension Center-Western Division, Eagle Lake, Texas 77434, USA.



1. Major rice areas of Asia.

and at Al Hafuf, Saudi Arabia, with less than 100 mm rainfall during the growing season. Rice is grown in regions with no impounded water and on floodplains in water 5 m deep. Temperatures during the growing season average 33°C at Sukkur, Pakistan, and 17°C at Otaru, Japan. Rice also grows under a broad range of solar radiation -- 25% potential in Burma and Thailand to 95% in Egypt.

The highest yields are generally obtained from high latitude areas, such as southeastern Australia, northern Japan, and Spain. Such high yields on one hand and the great diversity existing in the cultivated rices on the other illustrate man's and nature's selection in developing numerous cultivars, many of which have highly specific adaptation to different physical environments.

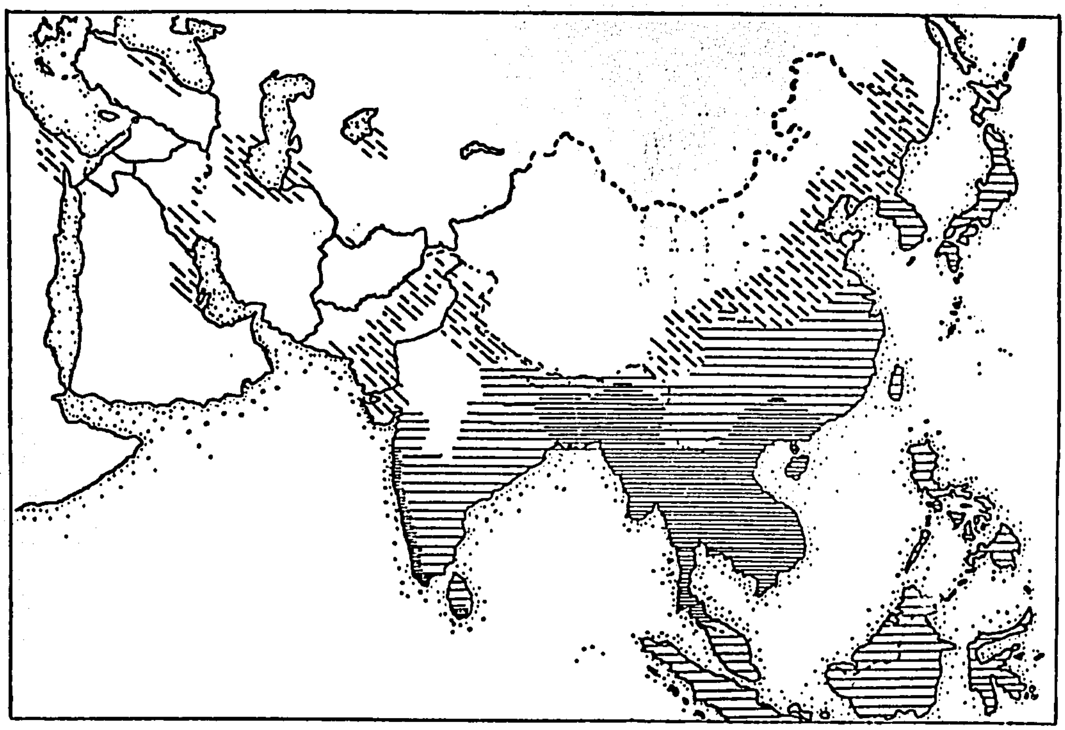
A GENERALIZED APPROACH TO CLIMATIC IMPACT

A generalized approach to climatic impact can be made with a method outlined by Huke (1976). The danger of such an approach is recognized, and this analysis simply provides a rough estimate of the impact climatic change may have on world rice production.

The Asian map of the major rice-producing areas was crudely divided into three climatic regions (Fig. 2). Area I is the core area of about 41 million ha, where modest crops are grown year after year with no need for climatic modification by man. Nature alone controls all the climatic parameters the crop requires. The worst problems encountered are insects and plant diseases. Yields are not large but are stable.

The second region -- Area III -- is the outer climatic limits of rice production in both the geographical and the climatic sense. Here, excellent crops can be produced each year when man controls at least one climatic parameter. The area is a reliable producer of good crops, and the most serious problems are energy costs. Energy for constructing and operating irrigation is a major factor. This area has temperature and growing season as limiting factors, but it also has the highest potential yields on a per-crop basis. Rice production is limited to about 6 million ha.

The third region -- the most serious problem area -- is the great transitional belt between the two extremes. This broad region, shown as Area II, comprises more than half of the world's rice production (75 million ha). Problems in



Area

- I — Areas where rice may be raised year after year with no climate modification by man.
- II — Important rice-producing areas where at least one parameter of climate is frequently less than ideal for successful crops.
- III — Areas where rice production is widely scattered and where climate must be modified to produce a crop.
- IV — Areas with no important production of rice.

Area	Rice area (million ha)	Yield (t/ha)	Production (million t)
I	41	1.6	65.6
II	75	2.3	172.5
III	6	4.6	27.6

2. Climate and rice (Huke 1976).

this zone include insects and diseases, but the most serious and least controlled is climatic variability, especially rainfall. A major portion of the rice crop is produced without microclimatic modification. Water control consists of simply ponding precipitation.

Superimposing the rice cultural systems as proposed by Barker (1972) (Table 1) onto Huke's model of climate and rice gives some general conclusions concerning changing rainfall patterns and world rice production (Table 2, 3). The statistics of Barker and Huke have been slightly modified to include rice production outside Asia.

Area I is predominantly rainfed wetland that accounts for 24% of the world's rice area but only 15% of the world's rice production. Its deepwater culture accounts for about 5% of the world's production. Double-cropping of rice is gaining popularity where supplemental irrigation is available during the dry season. The yields in Area I are characteristically low (1.6 t/ha).

Area II is the largest rice-producing region, encompassing most of the world's rainfed rice. It is highly susceptible to changes in rainfall patterns. Rainfed dryland rice is the lowest yielding and accounts for about 10% of the world's production. Area II has about 25% of the world's area and production of rain-

Table 1. Rice cultural systems based on water use.[a]

Culture	Crop Area (%)	Production (%)
Rainfed dryland	20	10
Rainfed wetland	50	42
Single crop (irrigated)	10	15
Double crop (irrigated)	10	25
Deep water	10	8

[a]Adapted from Barker (1972).

Table 2. Percentage of world rice area classified by water culture and climatic region.

Climatic region[b]	Area[a] (%)					
	Rainfed dryland	Rainfed wetland	Single crop (irrigated)	Double crop (irrigated)	Deepwater	Total
Area I	-	24	-	3	8	35
Area II	20	26	7	7	-	60
Area III	-	-	5	-	-	5
Total	20	50	12	10	8	100

[a]Based on world production from 140 million ha. [b]Adapted from Huke (1976) and Barker (1972).

Table 3. Percentage of world rice production classified by water culture and climatic region.

Climatic region[b]	Production[a] (%)					
	Rainfed dryland	Rainfed wetland	Single crop (irrigated)	Double crop (irrigated)	Deepwater	Total
Area I	-	15	-	5	5	25
Area II	10	25	10	20	-	65
Area III	-	-	10	-	-	10
Total	10	40	20	25	5	100

[a]Based on world production of 340 million t. [b]Adapted from Huke (1976) and Barker (1972).

fed wetland rice. To stabilize yields, single crops and double crops of irrigated rice are increasing in the area. About 65% of the world's production comes from Area II; average yields are about 2.3 t/ha.

Area III has predominantly irrigated single crops and the highest yields (4.6 t/ha). The growing season is the major limitation to rice production. Heavy use is made of fossil fuels for cultivation, irrigation, fertilization, and harvesting. Both capital inputs and returns are high. Area III includes the U.S., Australia, portions of Japan, the Mediterranean, portions of South America, and South Africa.

Every effort should be made to broaden crop tolerance for variable weather. This will have a long-range positive impact on crop response. Priorities established by man can modify any predictions made now. Therefore, only *conservative* estimates of the impact of climatic change are presented.

The parameters of possible climatic change by the year 1990 are temperature of ± 2°C, precipitation of ± 15%, and solar radiation of ± 8%.

INFLUENCE OF CLIMATIC CHANGES

Temperature

Temperature changes would dramatically influence the rice-growing regions of Areas II and III (Table 4). Since most of the rice in Area III is irrigated, temperature affects production through its influence on the length of the growing season. Temperatures as low as 15°C can cause sterility during reproduction (Satake 1976), and cool injury could occur in some years. If the growing season is long enough for rice production temperatures during the reproductive period would not be regionally limiting.

Stable rice production requires a growing season long enough for normal growth and development. A growing season that begins when temperatures rise above 15°C and ends when temperatures fall below 15°C represents the cooler limits for successful rice production. At these lower temperatures, plant growth and development will be slow even for early-maturing cultivars. A growing season of 150 days would be the lower limit for

Table 4. World rice production as influenced by temperature change.[a]

Temperature change (°C)	Deviation (%) from world production[b]			
	Area I	Area II	Area III	Total
-2	1	-7	-5	-11
-1	0	-3	-2	-5
-.5	0	0	0	0
+.5	0	2	2	4
+1	0	5	3	8
+2	-1	8	4	11

[a]Assuming present precipitation patterns remain constant. [b]Based on world production of 300 million t.

areas of direct-seeded rice and 125 days for areas of transplanted rice.

Each 1°C decrease in temperature will decrease the growing season by 10-14 days (Ramirez 1975). This reduction was used for prediction because rice is more sensitive to low temperatures than most other crops. A 0.5°C reduction will not seriously influence rice production in Area III. A 1.0°C reduction will reduce the growing season to a critical point in areas such as Hokkaido (Japan), northern Italy, Nepal, northern Bangledesh, India, northern California (USA), North Korea, and the northern portions of South Korea and China.

A 2°C reduction in temperature would reduce production in those areas and influence production in Japan, South Korea, India, East Pakistan, Spain, Turkey, and southern Australia, other portions of the U.S., high altitude regions of South America, and South Africa. While such a temperature change would be devastating to the rice economy locally, it would have only a minor effect (about 5% in Area III) on world production.

Increases in temperature will have a positive influence on production in Area III. The longer growing season would allow more flexibility in planting time and result in better utilization of solar radiation. This has been demonstrated in the Texas rice belt where early-maturing cultivars gave higher yields. Early planting of early-maturing cultivars takes advantage of expected maximum accumulative sunlight conditions during the stage when the crop requires maximum solar energy for high grain yields (Stansel 1975).

Temperature changes will have their greatest impact in Area II on double crop production. Low temperature will limit double-crop production during the winter. Double-crop areas in China, Taiwan, Philippines, and India would be affected most. If sufficient water were available, higher temperatures would expand double-crop production in these areas, and the single-crop irrigated areas of northern China and Japan located in Area II.

Temperature changes would have little influence on the rainfed cultures of Areas I and II. The deepwater cultures of Area I would not be significantly influenced by temperature change either. A temperature change of ± 2°C could alter world rice production by ± 11% .

Precipitation change

Changes in precipitation have complex and differential effects on world rice production (Table 5). Decreased precipitation would reduce the production of rainfed wetland rice but raise that of deepwater rice. The changes appear small, but the magnitude within a region can be great. A 15% reduction in rainfall could easily reduce rainfed dryland production by 30% but influence world production by only 3%. This could cause extensive regional shifts in rice production.

Precipitation change would affect rainfed dryland rice production most, followed by rainfed wetland. In these cultures, the relationship between production and precipitation is direct. The effect on irrigated single and double-cropped cultures would be less, because of their more stable water supply. Reductions in rainfall would be offset by increased solar radiation. Deepwater rice production is negatively correlated

Table 5. Precipitation-induced changes in world rice production by area and rice culture.

Precipitation change (%)	Change (%) in world rice production[a]								
	Area I rice culture				Area II rice culture				
					Rainfed		Irrigated		
	Rainfed wetland	Double crop	Deep-water	Total	Dryland	Wetland	Single crop	Double crop	Total
-15	-2.2	-0.3	0.7	-2.4	-3.0	-3.8	0.4	-0.8	-7.2
-10	-1.5	-0.2	0.5	-1.2	-2.0	-2.5	0.2	-0.5	-4.8
-5	-0.8	-0.1	0.3	-0.6	-1.0	-1.2	0.1	-0.2	-2.5
5	0.8	0.1	-0.3	0.6	1.0	1.2	-0.1	0.2	2.5
10	1.5	0.2	-0.5	1.2	2.0	2.5	-0.2	0.5	4.8
15	2.2	0.3	-0.7	2.4	3.0	3.8	-0.4	0.8	7.2

[a]Based on world production of 300 million t.

Table 6. World rice production as influenced by precipitation change.[a]

Precipitation change (%)	Deviation (%) from world production[b] Area I	Area II	Area III	Total
-15	-2	-7	1	-8
-10	-1	-5	0	-6
-5	0	-2	0	-2
+5	0	2	0	2
+10	1	5	0	6
+15	2	7	-1	8

[a]Assuming present temperature patterns remain constant. [b]Based on world production of 300 million t.

with precipitation because flood depth influences the yield of floating rices.

The total effects of precipitation on world rice production are summarized in Table 6. An estimated precipitation change of ± 15% would alter world production by ± 8%. The impact in some localities would be severe, but would be offset by differential effects on other rice cultures.

Temperature-precipitation interaction

The effects of changes in temperature and precipitation are largely additive. Temperature influences the growing season, while water supply influences cultural practices. Temperature has less influence on soil moisture depletion by the plant because rice grows in its own reservoir of water. It grows in areas where other crops do not grow well because of excessive moisture during the growing season. Many irrigated rice soils have poor structural characteristics that are unfavorable for other crops. Thus, rice will continue to be grown in these areas because alternate crops are not as productive.

World rice production

Temperature change affects world rice production by altering the length of the growing season, and thus limiting the geographical areas in which rice could be grown. Where the growing season is adequate, temperature change would only slightly influence yield. The growing season limits would be mean temperatures above 15°C, without temperatures falling below 10°C for more than 3 consecutive days.

The reduction of mean temperatures in nontropical areas would shorten the growing season. The subsequent slow rate of plant growth and development would require a longer growing season. Because each 1°C decrease in mean temperature would reduce the growing season by 10 to 14 days, each cultivar would require from 7 to 11 days additional time from seeding or transplanting to maturity. Thus a 1°C change in mean temperature would produce a gross change of 17 to 25 days in *effective* growing season. In areas where reduced temperatures limit the growing season, genetic diversity is available for the development of cool-tolerant cultivars.

Increases in mean temperatures would generally increase the areas where rice could be grown. However, rice yields could decrease in the tropics. Temperature changes could also cause insect and disease problems.

Irrigated cultural systems would be influenced less by precipitation change than other cultures. However, precipitation patterns influence the amount of water available for irrigation. The effect -- assumed to be minor -- should be studied more.

Reduced precipitation results in increased solar radiation. Where water is not limiting, the increase in solar radiation would result in increased yields. A 1% change in solar energy available to the plant community would result in a 1.4% change in production if other factors were not limiting. If a 1% change in precipitation would produce at least a 0.5% change in solar energy reaching the crop, the yield potential change would be large. In rainfed dryland, rainfed wetland, and deepwater cultures, changes in solar energy would not have a large influence on yield because other factors are more limiting.

Using the cultural systems proposed by Barker and the model of climate and rice by Huke, a rough estimate of the impact of climatic change was made for

Table 7. Deviation from the world rice production base resulting from changes in temperature and precipitation.[a]

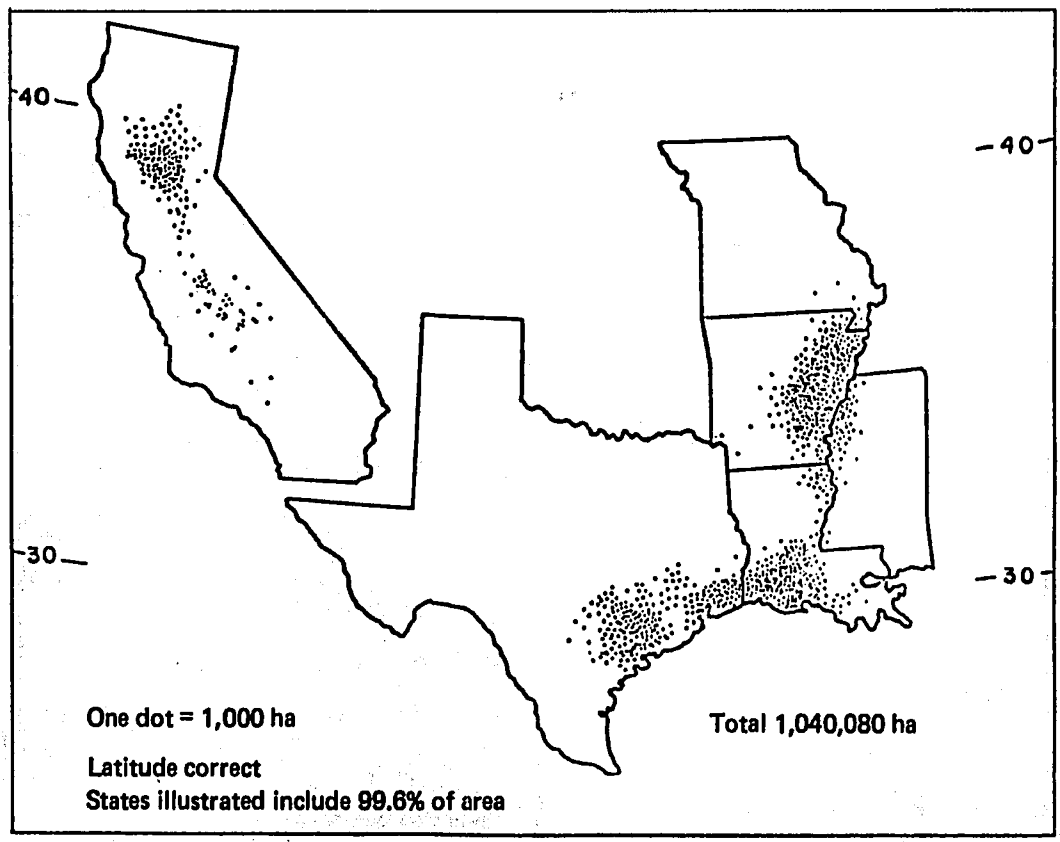
Precipitation change (%)	Deviation (%) at a temperature change of -2°C	-1°C	-.5°C	0	+.5°C	+1°C	+2°C
-15	-19	-13	-8	-8	-4	0	3
-10	-17	-11	-6	-6	-2	2	5
-5	-13	-7	-2	-2	2	6	9
0	-11	-5	0	0	4	8	11
+5	-9	-3	2	2	6	10	13
+10	-5	1	6	6	10	14	17
+15	-3	3	8	8	12	16	19

[a]Based on world production of 300 million t.

each cell combination (Table 7). Rice production from water culture systems within a climatic area was influenced differently by a change in temperature, precipitation, and solar radiation. By this rough technique, it was estimated that world rice production could change by ± 19% with a ± 2°C in temperature and a ± 15% change in precipitation. Such a decrease in temperature and precipitation could be devastating, but increases would make it much easier for man to feed himself. It is important to note that even modest changes of ± 0.5°C temperature and ± 10% precipitation could result in -6% or +10% change in world rice production.

CLIMATIC IMPACT IN THE UNITED STATES

The United States grows about 1.5% of the world's rice, but accounts for about



3. United States rice area, 1974.

20% of the world's export market. Rice is generally either the number one or number two cash crop in Louisiana and Arkansas. In Texas, rice is grown in 17 of 254 counties, but is either the third or fourth in cash value. The distribution of rice production in the United States is shown in Figure 3.

Temperature

The impact of temperature change on rice production in the United States would be similar to that on world production. U.S. rice is in climatic region III, and is very sensitive to temperature change that alters the length of the growing season and the rate of rice growth and development.

The cultivars grown in the southern rice region roughly fit a growing season with temperatures above 17°C. Cultivars tolerant of cooler temperatures in California have adapted to a 16°C growing season. Even if new cultivars that could grow at the 15°C lower level were developed, their slower growth rate and severely restricted growing season would severely reduce production.

The California rice area is affected by seasonal shifts in temperature. Cold irrigation water adds to the cool weather sensitivity, especially in the north. Data from the U.S. Weather Bureau in Sacramento indicate temperatures 1.2°C below normal for May and October of 1971. The 1971 average state yields for California were 6% lower than the 1969-73 mean and 9% lower than the 1972-73 mean. Cool temperatures in late spring and early fall contributed to this yield loss, although mean temperatures for the growing season were only 0.2°C below normal. This indicates the sensitivity of yield potential to even modest shifts in mean temperature. Similar circumstances were observed for 1973 yields in Texas; however, increased precipitation played a role in suppressing yields by 14%.

Increases in mean temperature would be beneficial in all the United States rice-producing areas, particularly California and Arkansas. The flexibility in planting dates, better control of cultural inputs, and increased utilization of available sunlight would result in increasing yields and yield stability.

Precipitation

Precipitation would have little direct effect on production as all rice grown in the United States is irrigated. However, it would influence the availability of irrigation water. From 80 to 85% of United States rice is irrigated from surface water runoff resources. Precipitation influences planting dates and rice culture, and the amount of sunlight available to the crop.

It is assumed that a 15% reduction in precipitation by 1990 would change water availability by less than 7%, increased water use efficiency would offset this change. Additional water could encourage some rice acreage expansion, but the cost of irrigation distribution systems may be prohibitive.

Precipitation increases combined with decreased temperatures, could reduce yields substantially. Characteristically, increased precipitation during the fall, winter, and spring months could reduce the chances for early land preparation required for optimum planting dates. Precipitation changes have their greatest impact on rice production by altering the levels of sunlight available for rice growth (Stansel 1975).

Summary

Man has the ability and tools to adjust rice production to a changing climate. But how well he meets the challenge of climatic change depends primarily on the research goals and emphasis given to research programs. Given a 2°C reduction in mean temperature and a 15% increase in precipitation, yields would be reduced 18% and the United States rice industry could not exist in 1990 with today's cultivars (Table 8). First, there would be little rice industry in California (25% of present), and if the industry survived in Arkansas, production would be cut by 50%. Rice production could survive in Texas and Louisiana, but yields would be reduced by 20%.

OVERVIEW

The effect of climatic change could be devastating to world and U.S. rice production. Only through concerted research efforts to develop cool-tolerant varieties can man hope to feed himself in a cooling environment. Even if climate does not change, the development of cool-season cultivars would give more flexibility in rice culture and possibly more stabilized and higher production.

Within limits, research can meet the challenge of a changing climate, but

Table 8. Deviation from U.S. average production of rice as influenced by changes in precipitation and temperature.[a]

Precipitation change (%)	Deviation (%) at a temperature change of						
	-2°C	-1°C	-.5°C	0	+.5°C	+1°C	+2°C
-15	2	5	8	8	11	15	20
-10	-1	2	5	6	8	12	18
-5	-4	-1	2	2	5	9	14
0	-9	-4	-1	0	4	7	12
+5	-9	-6	-3	-2	0	4	9
+10	-14	-10	-7	-6	-3	0	6
+15	-18	-14	10	-9	-6	-2	3

[a]Based on U.S. production of 5 million t.

the goals must be clearly outlined and proper emphasis placed to achieve these goals.

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Climatically induced rice production variations and their influence on society

K. Takahashi

The 35-year Brückner cycle, which seems to be caused by atmospheric oscillation due to changes in solar activity, is traceable in the frequency of the world's famines. Historical records from the Edo Period (1600-1868) in Japan suggest that cyclical weather changes affected rice production and caused severe famines with resulting population decreases about 20 years thereafter.

In Japan, as in many Southeast Asian countries, rice is the most important agricultural product. Japan's economy formerly depended almost entirely on rice production; however, industrial development has considerably reduced the crop's importance.

Annual rice production in Japan is influenced mainly by summer air temperatures and slightly by precipitation because Japan is in the middle latitudes at the northern extreme for rice production.

The globally cold climate during the Edo Period (1600-1868) is often referred to as a little ice age. During this time, frequent cool summers brought poor harvests whose impact was serious because Japan was isolated from the rest of the world. Decreased rice production meant a decreased food supply, and, not rarely, many died of starvation.

The world's severe famines, however, are brought about mainly by droughts that cause poor harvests. Historical climatic records show that droughts occur more frequently in some periods than in others, appearing alternately in an approximately 35-year series known as the Brückner cycle.

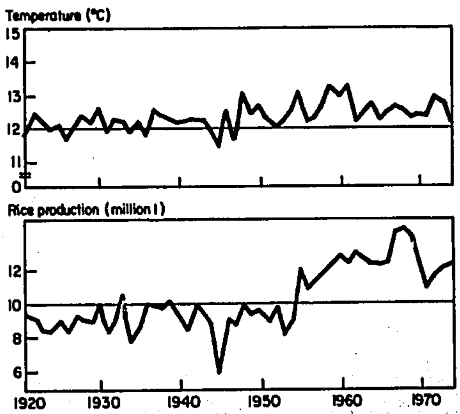
YEARLY RICE PRODUCTION AND AIR TEMPERATURE VARIATIONS IN JAPAN

Figure 1 shows variations in Japan's annual rice production and annual air temperature. The temperatures are near the mean at 23 stations. The figures clearly indicate the remarkably increased rice production in the last several decades -- about 2.5 times larger than a century ago.

Rice field acreage has remained roughly the same during the last hundred years and increased annual rice production has resulted from the development of improved agricultural techniques that have increased rice yield per unit area.

Short-period rice production variations are caused mainly by yearly air temperature variations. Rice production decreases when air temperature is low. Daigo (1940) calculated correlation coefficients between annual rice production and monthly air temperature in northern Japan to be about 0.7 for August and 0.5 for July.

Such relationships may have changed today because of improved agricultural techniques; but although climatic anoma-



1. Secular change of air temperature and rice production in Japan.

Waseda University.

lies may seem to influence rice production less, the influence of air temperature variation on rice production has never ceased. This is apparent from the fact that, even in recent years, rice production and air temperature as a whole change in a parallel manner, as the two curves in Figure 1 illustrate.

The standard deviation for annual air temperature is about 0.5°C. Between 1956 and 1973, the percentage variation of the standard deviation for rice production was about 8%. This rice production variation contains, however, the increase created by agricultural development. If this effect is subtracted, rice production percentage variation can be estimated at about 5%. Assuming that such variation is caused by temperature variations, a 1°C decrease of air temperature would conceivably result in a 10% decrease in rice production.

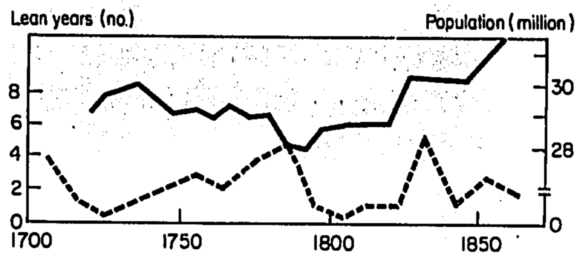
Temperature change due to climatic change is never small compared with yearly annual air temperature variations. At present, Japan's air temperature is 1°C higher than at the beginning of this century, and the increase in rice production due to the rise in air temperature is estimated at about 10%.

THE RELATION BETWEEN SEVERE FAMINE AND POPULATION IN OLD JAPAN

Japan was closed to the rest of the world during the Edo Period (1600-1868). Virtually no trade with other countries occurred; thus, poor harvests meant an immediate decrease of food -- severe famines, and decreased population.

Japan was comparatively peaceful in those days and much historical data on famines and population are preserved. Figure 2 shows the population and number of poor harvests in one decade during the Edo Period (Takahashi 1976). Because Japan's poor harvests are caused mainly by cool summers, the number of poor harvests also suggests temperature variations in the country during the same period.

Figure 2 also indicates that the population of 30 million remained nearly stationary, decreasing slightly about 20 years after a lean year. This relationship is theoretically derived by assuming a logistic equation for population increase, an 80-year cycle for climatic variation corresponding to the apparent cycle of lean years in Figure 2, and an amplitude of about 10% for rice production variations. The numerical



2. Number of lean years in a decade and population during the Edo Period.

integration shows that population changes resemble rice production changes with a 20-year lag and that the variation amplitude is about 2-3%. The result roughly agrees with value curves actually observed.

Such a relationship cannot be observed after the Edo Period because rapid economic growth, which resulted from Japan's contact with the rest of the world, led to a rapid increase in the population.

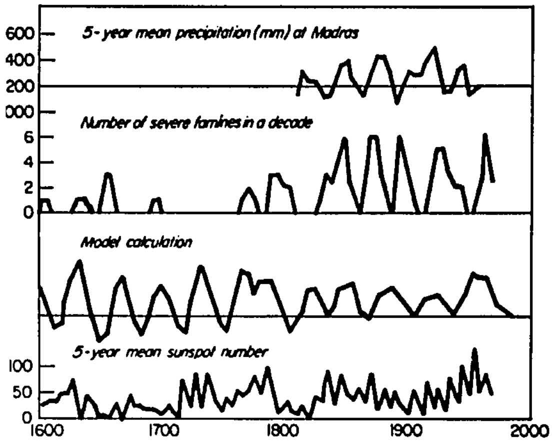
THE BRÜCKNER CYCLE IN SECULAR CHANGES OF SEVERE FAMINE AND DROUGHT WORLDWIDE

My analysis so far has been based mainly on Japanese data. In Table 1, the data showing the number of severely lean years in a decade worldwide came mainly from Cornell (1976).

Severe famines caused by droughts occurred mainly in China, India, and the

Table 1. Number of severe famine years in the world.

Famine year (no.)	Century 1600	1700	1800	1900
0	1	0	2	4
5	1	0	2	1
10	0	0	0	0
15	0	0	0	0
20	0	0	0	3
25	0	0	0	5
30	1	0	1	5
35	1	0	3	3
40	0	0	2	2
45	0	0	4	2
50	3	0	6	0
55	3	0	2	0
60	0	0	0	2
65	0	1	3	6
70	0	2	6	4
75	0	1	6	
80	0	0	3	
85	0	0	0	
90	1	3	3	
95	1	3	6	



3. Simulation of the Brückner cycle.

USSR, with droughts being much more important globally than cool summers.

Figure 3 shows secular changes for the famine years in a decade. Lean years are frequent in some decades and rare in others, with increases and decreases occurring alternately in a roughly 35-year cycle.

This climatic cycle, well-known as the Brückner cycle, is distinct in the 5-year mean annual precipitation in Madras, India (Fig. 3). Severe famines are frequent when precipitation in Madras is low.

The mechanism of the Brückner cycle is not yet clear. I analyzed the cycle in 1969 using northern hemisphere meteorological data and found that the pressure over high latitude areas changes cyclically in the cycle and that Madras precipitation decreases when high latitude pressure rises. Thus, the Brückner cycle seems to be generated by general circulation oscillation caused by some external force, possibly the influence of changes in solar activity.

I simulated the Brückner cycle using a simple model. Oscillation of the general circulation is expressed by a simple harmonic oscillator with a period of 35 years and a damping ratio of 0.71. Sunspots, observed since the mid-eighteenth century, are one index of solar activity. It is assumed that the 5-year mean value of the annual numbers of sunspots is one index of the external forces exciting oscillation. The mode of oscillation can then be calculated.

Results of such a calculation are shown in Figure 3. The three curves of calculated values, observed values of the number of severe famines, and precipitation in Madras are similar, especially in their peaks and phases. Accordingly, this hypothesis seems correct, at least for the first approximation. However, further research is needed to confirm it.

CONCLUSION

From this analysis, it is clear that the influence of climatic change on rice production and, consequently, on society, is never small. Severe famines caused by droughts have occurred cyclically, as in the Brückner cycle, in India, North Africa and the USSR around 1970 corresponding to the bottom of this cycle.

Assuming that such a cycle applies in the future, severe famines may be expected to plague the world early in the 21st century.

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Crop weather analysis based on minimum meteorological data for multiple cropping in the humid lowland tropics

J. J. Riley

The demand for more food has placed pressure on farmers and agricultural researchers to intensify and diversify tropical crop production systems. Crops are being grown on marginal lands and in seasons with less than optimal environments. Tropical weather systems that bring rains are often violent and meteorological stations to gage their effect, sparse. A method of evaluating minimum environmental data to determine optimal cropping patterns for given sites in the lowland humid tropics is presented.

It is said in the Asian tropics that "everything begins with rice." Rice is the principal staple food for the region's 2 billion inhabitants and its cultivation is the primary employment activity. The abundant rainfall permits the production of at least one rice crop a year without irrigation on about half of the region's alluvial plains. For centuries one rice crop a year was sufficient to feed the population, and man as well as rice flourished in this region. But to survive, both man and rice require an assured supply of water. As a result, human settlements and (rainfed) rice production reflect precipitation patterns in the tropical lowlands. For example, in the Indochina peninsula and adjacent areas, population density, rainfall intensity and rice farming reach a global peak (Huke 1976, Riley 1978a).

The demand for more food has stimulated the cropping of marginal lands, extension of growing seasons (including planting under less favorable environmental conditions), introduction of new crop species, and development of improved varieties (Wortman and Cummings Jr 1978). As of 1975 only one-fourth of the Asian rice fields were planted to new high yielding varieties (IRRI 1976). A report by the Asian Development Bank (1971) states: ". . . the Green Revolution based on the Japan-Taiwan model is not likely to succeed unless the small farmers of Southeast Asia are prepared to work, as their counterparts in those countries, growing a succession of crops throughout the year." For year-round crop production, varieties, inputs, and planting dates that make best use of available natural resources must be selected. Tropical agricultural research must focus on whole-year cropping systems to increase annual farmer productivity (Riley and Menegay 1978, Carandang 1975a).

The idea of using climatic data for crop planning in the Asian tropics is not new. Two excellent papers on this subject by Brammer, and Oldeman and Suardi were published recently (IRRI 1977). However, the effect of the violent nature of the weather systems that bring rain is usually omitted. At Tainan in southern Taiwan, it is estimated that more than 80% of the annual rainfall is derived from thunderstorms (Riley 1978b). Severe tropical cyclones wreak havoc on lives, property, and crops throughout the tropics except in regions adjacent to the equator. Annually, three cyclones pass over or near Taiwan and more than twice that number typically cross the Philippines (Chiang 1974, PCARR 1977). Carandang (1975b) described the important effect typhoons have on Philippine cropping systems.

A simple means of incorporating the frequency of severe storms into environmental analyses for crop planning is presented in this paper. A more

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complete description of the proposed methodology is given in Riley (1979).

This paper includes analysis of cropping patterns for rice (*Oryza sativa*) and the vegetable species being given attention by The Asian Vegetable Research and Development Center (AVRDC) in Taiwan, namely: soybean *Glycine max*, sweet potato *Ipomoea batatas*, mung bean *Vigna radiata*, tomato *Lycopersicon esculentum*, white potato *Solanum tuberosum*, and Chinese cabbage *Brassica campestris* spp. *pekinensis*.

It is assumed that sufficient water is available throughout the year to meet the production needs of these crops and that yields are more severely affected by too much, rather than by too little, water.

DATA REQUIREMENTS

There is a paucity of weather data in the tropics. Therefore, the method of analysis presented is based on the evaluation of temperature and rainfall, usually measured by even the smallest weather observation stations. The method also assumes that the major seasonal variation of severe storms and solar radiation can be estimated from data or by experienced observers. This analytical approach considers relative variation generally more important than absolute amounts.

The relative monthly variation of the following need to be recorded or estimated:

1. solar radiation (cal/cm^2);
2. maximum and minimum temperatures (°C);
3. rainfall (mm);
4. severe storm frequency (%); and
5. the environmental limits to normal growth for each crop.

Solar radiation data are the most difficult to find, and a means of estimating the solar radiation from sunshine (%) records, which are more frequently available, is given. If sunshine data are missing, relative monthly cloudiness could be substituted.

Data for Kaohsiung, Taiwan (22°37'N lat. and 120°16'E long.), and Los Baños, Laguna, Philippines (14°10'N lat. and 121°15'E long.), were used to illustrate the method of analysis (Table 1, 2).

The environmental constraints to normal growth of rice and selected vegetable crops are given in Table 3. Due to the nature of the available data, the limits in some cases are stated differently for Kaohsiung and Los Baños. The aim is to state approximately equivalent measurements of growth constraints in each case.

METHOD OF ANALYSIS

The environmental data correspond to crop growth constraints for either a whole crop or a particular portion of a cropping period (i.e., most often harvest time). The former are illustrated (Table 4) by the tabulation of accumulated solar radiation in Kaohsiung for crop periods ranging from 1 to 5 months. An example of the latter is the relative typhoon threat in the last month of crop production periods ranging from one to five months in Laguna Province, Philippine (Table 5). Similar tables are prepared for maximum and minimum temperatures, and precipitation and thunderstorm probability at harvest or mean number of rainy days per month during harvest. All pertinent environmental data are summarized for crop periods ranging from 2 to 5 months. Examples for 3- and 4-month crops are given in Tables 6 and 7. Note that the values for the whole cropping period, the last month, or the last 2 months are entered under the month in which the crop is planted. This permits easy comparison of the effect on a given variable of advancing or delaying planting by one or more months.

Environmental data summarized by crop length (Tables 6 and 7) can be used in conjunction with the biological tolerance limits in Table 3 to determine the planting months that meet the specified growing conditions for each crop. These are then summarized as in Tables 8 and 9. With the latter tables, it is relatively easy to scan a column for a given planting month and tell whether a particular crop meets all, some, or none of the specified criteria. The selection of the best planting options is subjective. More weight to one or another factor can be given based on knowledge of crop production. In general, the most important factor is listed at the top of the table followed by factors of equal or lesser importance. Further research is needed to determine the actual relative importance of the five environmental factors on the growth of each crop. The optimal cropping patterns for the selected crops for Los Baños and Kaohsiung are given in Tables 10-13.

Other data can be included to

Table 1. Environmental data for Kaohsiung, Taiwan, Republic of China (lat. 22°37'N).

	Source	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direct observation													
Sunshine (%)	Central Weather Bureau 1974[a]	54	56	53	54	56	47	51	48	58	63	58	54
Max temp (°C)	"	23.1	23.8	26.0	28.6	31.0	31.2	31.6	31.3	31.2	29.9	27.4	24.4
Min temp (°C)	"	15.0	15.5	18.2	21.2	24.1	25.0	25.4	25.2	24.7	22.6	19.8	16.7
Rainfall (mm)	"	10.8	16.4	39.9	55.5	155.1	426.4	433.5	370.1	158.4	40.9	22.0	13.0
Severe storm frequency													
Thunderstorms/day (%)	"	0.3	0.6	2.3	4.7	10.3	16.3	22.6	24.5	15.0	3.5	0.3	0
Typhoons/mo (%)	Chiang 1974[b]	0	0	0	0	5	5	15	20	0	0	0	0
Calculated data													
Mean daily solar radiation[c]		258	347	339	389	411	362	376	336	289	365	279	242

[a]Mean data 1932–70. [b]Mean data 1951–71. [c]Mean daily solar radiation at the earth's surface in a cloudless sky (Weast 1976) x sunshine (%) (see Table 4).

Table 2. Environmental data for Los Baños, Laguna, Philippines (lat. 14°10'N).

	Source	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direct observation													
Solar radiation (cal/cm^2 per day)	Yoshida & Parao[a] 1976	336	432	479	568	500	442	402	373	379	363	317	295
Max temp (°C)	" [b]	29.3	30.2	31.9	33.9	34.8	33.2	31.9	31.5	31.3	30.8	29.9	29.2
Min temp (°C)	" [b]	21.2	20.6	21.7	22.9	23.9	23.8	23.6	23.4	23.3	22.8	22.4	22.1
Rainfall (mm)	UPLB 1976 [c]	51.0	23.9	26.4	37.6	153.4	217.4	279.6	264.4	243.6	247.4	276.6	167.1
Severe storm frequency													
Av monthly occurrence of typhoons in the Philippines (M) (%)	PCARR 1977 [d]	1.3	0.01	0.01	1.3	2.7	20.0	14.0	17.3	17.3	8.0	12.0	5.3
Distance of mean monthly typhoon track from Laguna Province (D) (km)	PCARR 1977 [d]	440 S	360 S	360 S	220 S	40 S	180 S	340 N	470 N	240 N	200 S	210 S	260 S
Mean no. of rainy days/mo	UPLB 1976 [c]	12	7	6	6	12	17	21	20	20	18	18	17
Calculated data													
Typhoon severity index (I)[e]		–	–	–	4.5	25.0	5.6	–	–	4.2	5.0	4.8	–
Relative typhoon threat[f] (for Laguna) (%)		0	0	0	1.7	18.7	31.6	0	0	20.5	11.3	16.2	0

[a]Mean data, IRRI, 1966–70. [b]Mean data, UPLB, 1966–70. [c]Mean data, UPLB, 1925–76. [d]Mean data, 1900–75.
[e]Typhoon severity index (I) = $\frac{1000 \text{ km}}{D < 250 \text{ km}}$. [f]Relative typhoon threat for a given month (%) = $\frac{M \times I}{\Sigma(m \times I) \text{ (for year)}} \times 100$.

Table 3. Environmental constraints[a] to normal growth of rice and selected vegetable crops.

Parameter	Two-month crops: Chinese Cabbage HS	Two-month crops: Chinese Cabbage HT	Three-month crops: Chinese Cabbage HS	Chinese Cabbage HT	White Potato HS	White Potato HT	Mung Bean	Soybean	Four-month crops: Soybean	Sweet Potato	Rice	Five-month crops: Sweet Potato	Tomato HS	Tomato HT
Radiation (cal/cm²)														
Whole crop	M	H	M	H	–	–	H	–	–	–	–	H	H	H
Last month	–	–	–	–	H	H	–	H	H	H	H	–	–	–
Temperature (°C)														
Max	25[b]	30[c]	25[b]	30[c]	20[b]	30[c]	35	30[c]	30[c]	35	35	35	25[b]	35
Min	10	20[e]	10	20[d]	15	15	20	15	15	10	15	10	15	15
Acceptable typhoon probability (%)[e]														
Whole crop	5	5	5	5	10	10	5	5	5	25	65	25	5	5
Last 2 mo	5	5	5	5	5	5	0	0	0	20	15	20	0	0
Last month	0	0	0	0	5	5	0	0	0	20	5	20	0	0
Tolerable precipitation (mm)														
Whole crop	M	M	M	M	M	M	M	M	M	H	H	H	M	M
Harvest period	–	–	–	–	M	M	L	L	L	M	M	M	M	M
Mean no. of rainy days/mo during harvest[f]	15	15	15	15	15	15	7	7	7	20	20	20	7	7
Allowable thunderstorm probability at harvest (%)[g] [g]	5	5	5	5	5	5	1	1	1	15	15	15	1	1
Harvest months	2	2	3	3	3	3	2,3	3	4	4	4	5	4,5	4,5

[a]Sources: (Central Weather Bureau 1974, Chiang 1974, Tanaka 1976, UPLB 1976, Kuo 1978). H = high, M = moderate, L = low, HS = heat sensitive, HT = heat tolerant. [b]Mean monthly maximum temperature never this low at Los Baños. Therefore, HS tomato, white potato, and Chinese cabbage are unsuitable for planting anytime in Los Baños. [c]Considered to be too restrictive for Los Baños. [d]Replaced by 32°C for Los Baños. [e]For Los Baños figures represent relative typhoon threat. [f]For Los Baños. [g]For Kaohsiung.

Table 4. Estimated accumulative solar radiation for 1- to 5-month crops. Kaohsiung, Taiwan, Republic of China.

Planting month	Sunshine (%)	Clear sky radiation 22.5°N (cal/cm²)	Estimated solar radiation[a] (cal/cm²)				
			1-mo crop	2-mo[b] crop	3-mo[b] crop	4-mo[b] crop	5-mo[b] crop
Jan	54	478	258	605	944	1,333	1,747
Feb	56	620	347	686	1,075	1,486	1,848
Mar	53	640	339	827	1,139	1,501	1,877
Apr	54	720	389	800	1,162	1,538	1,874
May	56	734	411	773	1,149	1,485	1,874
Jun	47	770	362	738	1,074	1,463	1,828
Jul	51	737	376	712	1,101	1,466	1,763
Aug	48	700	336	725	1,090	1,387	1,629
Sep	58	670	289	754	1,051	1,293	1,551
Oct	63	579	365	662	904	1,162	1,509
Nov	58	512	297	539	797	1,144	1,483
Dec	54	448	242	500	847	1,186	1,575

[a]Estimated solar radiation = sunshine (%) x clear sky radiation. In Tainan, Taiwan, this method of estimating solar radiation was found to underestimate the observed values (TSRI 1974) for 1969-70 by about 80 cal/cm² per day. [b]The accumulative solar radiation for crops ranging in length from 2 to 5 months was approximated by adding the mean values of daily radiation for each month. Source: Table 1

Table 5. Typhoon threat in the last month of 1- to 5-mo crops. Laguna, Philippines.[a]

Planting month	Typhoon threat (%)				
	1-mo crop	2-mo crop	3-mo crop	4-mo crop	5-mo crop
Jan	0	0	0	2	20
Feb	0	0	2	20	30
Mar	0	2	20	30	0
Apr	2	20	30	0	0
May	20	30	0	0	20
Jun	30	0	0	20	10
Jul	0	0	20	10	15
Aug	0	20	10	15	0
Sep	20	10	15	0	0
Oct	10	15	0	0	0
Nov	15	0	0	0	0
Dec	0	0	0	0	2

[a]Source: Table 2.

Table 6. Summary of environmental data for 3-mo crop planted in month indicated. Los Baños, Laguna, Philippines.[a]

Environmental data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (cal/cm²)												
Whole crop	1247	1479	1447	1510	1344	1217	1154	1115	1059	975	948	1063
Last month	479	568	500	442	402	373	379	363	317	295	336	432
Temperature (°C)												
Max	31.9	33.9	34.8	34.8	34.8	33.2	31.9	31.5	31.3	30.8	29.9	30.2
Min	20.6	20.6	21.7	22.9	23.6	23.4	23.3	22.8	22.4	22.2	21.2	20.6
Typhoon threat (%)												
Whole crop	0	2	22	52	50	30	20	30	45	25	15	0
Last 2 mo	0	2	22	50	30	0	20	30	25	15	0	0
Last month	0	2	20	30	0	0	20	10	15	0	0	0
Precipitation (mm)												
Whole crop	101.3	87.9	217.4	408.4	650.4	761.4	787.6	755.4	767.6	691.1	494.7	242.0
Harvest periods												
Last month	26.4	37.6	153.4	217.4	279.6	264.4	243.6	247.4	276.6	167.1	51.0	23.9
Last 2 mo	50.3	64.0	191.0	370.8	497.0	544.0	508.0	491.0	524.0	443.7	218.1	74.9
Mean no. of rainy days per month												
Last month	6	6	12	17	12	20	20	18	18	17	12	7
Last 2 mo	6	6	9	14	14	16	20	19	18	18	14	10

[a]Sources: Tables 2, 5, and other tables similar to Table 5 but not shown here.

Table 7. Summary of environmental data for 4-mo crop planted in month indicated. Kaohsiung, Taiwan, Republic of China.[a]

Environmental data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (cal/cm²)												
Whole crop	1,333	1,486	1,501	1,538	1,485	1,463	1,466	1,387	1,293	1,162	1,144	1,186
Last month	389	411	362	376	336	389	365	297	242	258	347	339
Temperature (°C)												
Max	24.5	27.2	27.8	28.2	28.2	28.2	28.2	27.9	27.5	25.7	23.2	21.7
Min	18.6	19.2	21.7	24.5	27.2	27.5	25.7	23.2	20.1	18.6	18.6	18.6
Typhoon probability (%)												
Whole crop	0	5	10	25	45	40	35	20	0	0	0	0
Last 2 mo	0	5	10	20	35	20	0	0	0	0	0	0
Last month	0	5	5	15	20	0	0	0	0	0	0	0
Precipitation (mm)												
Whole crop	122.6	266.9	676.9	1,080.5	1,385.1	1,388.4	1,002.9	591.4	234.3	86.7	62.2	80.1
Harvest periods												
Last month	55.5	155.1	426.4	433.5	270.1	158.4	40.9	20.0	13.0	10.8	16.4	39.9
Thunderstorm probability at harvest (%)	4.7	10.3	16.3	22.6	24.5	15.0	3.5	0.3	0	0.3	0.6	2.3

[a]Source: Tables 1, 4, and other tables similar to Table 4 but not shown here.

Table 8. Evaluation of environmental boundary conditions for 3-mo crop, planted in month indicated. Los Baños, Laguna, Philippines.[a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (cal/cm^2)												
Whole crop												
R $\geq$ 1240 (high)	MMMM	MMMM	MMMM	MMMM	MMMM							
Last month												
R $\geq$ 430 (high)	SSSS	SSSS	SSSS	SSSS								SSSS
Temperature (°C)												
32 $\geq$ T $\geq$ 15	SSSS						SSSS	SSSS	SSSS	SSSS	SSSS	SSSS
35 $\geq$ T $\geq$ 20	MMMM	MMMM	MMMM	MMMM	MMMM	MMMM	MMMM	MMMM	MMMM	MMMM	MMMM	MMMM
Typhoon threat (%)												
Whole crop t $\leq$ 5	MSMS	MSMS										MSMS
Last 2 mo t = 0	MSMS					MSMS					MSMS	MSMS
Last month t = 0	MSMS				MSMS	MSMS				MSMS	MSMS	MSMS
Precipitation (mm)												
Whole crop r $\leq$ 250 mm (moderate)	MSMS	MSMS	MSMS									MSMS
Harvest periods												
Last month r $\leq$ 100 mm	SSSS	SSSS									SSSS	SSSS
Last 2 mo r $\leq$ 100 mm (light)	MMMM	MMMM										MMMM
Mean no. of rainy days per month												
Last month d $\leq$ 7	SSSS	SSSS										SSSS
Last 2 mo d $\leq$ 7	MMMM	MMMM										
Best planting options												
Mung bean	1	2				3						4
Soybean	1	3									4	2

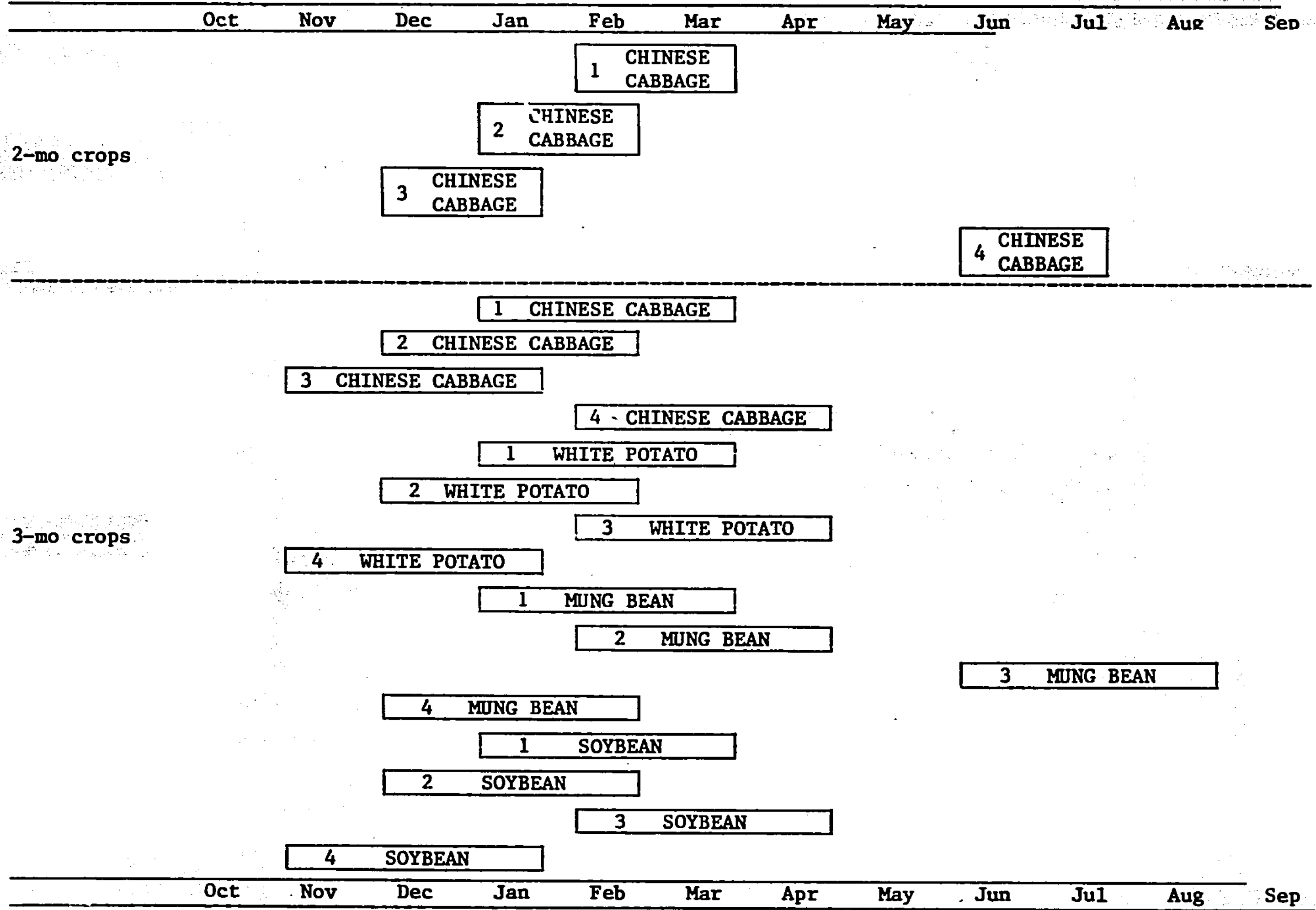
[a]Sources: Tables 3 & 6. M = mung bean, S = soybean. The planting months with the highest solar radiation for the whole crop or the last month, as shown in Table 6 are underscored.

Table 9. Evaluation of environmental boundary conditions for 4-mo crop, planted in month indicated. Kaohsiung, Taiwan, Republic of China.[a]

Environmental data		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (cal/cm²)													
Last month (H) $\geq$ 350		XXXX	XXXX	XXXX	XXXX		XXXX	XXXX[a]					
Temperature (°C)													
$15 \leq S \leq 30$													
$10 \leq E \leq 35$		XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX
$15 \leq R \leq 35$													
Typhoon probability (%)													
Whole crop	$S \leq 5$	SSSS	SSSS							SSSS	SSSS	SSSS	SSSS
	$E \leq 25$	EEEE	EEEE	EEEE	EEEE				EEEE	EEEE	EEEE	EEEE	EEEE
	$R \leq 65$	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR
Last 2 mo	$S = 0$	SSSS						SSSS	SSSS	SSSS	SSSS	SSSS	SSSS
	$E \leq 20$	EEEE	EEEE	EEEE	EEEE		EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE
	$R \leq 15$	RRRR	RRRR	RRRR				RRRR	RRRR	RRRR	RRRR	RRRR	RRRR
Last month	$S = 0$	SSSS					SSSS	SSSS	SSSS	SSSS	SSSS	SSSS	SSSS
	$E \leq 20$	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE
	$R \leq 5$	RRRR	RRRR	RRRR			RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR
Precipitation (mm)													
Last month	$S \leq 65$ (L)	SSSS						SSSS	SSSS	SSSS	SSSS	SSSS	SSSS
	$E \leq 160$(M)	EEEE	EEEE				EEEE	EEEE	EEEE	EEEE	EEEE	EEEE	EEEE
	$R \leq 160$(M)	RRRR	RRRR				RRRR	RRRR	RRRR	RRRR	RRRR	RRRR	RRRR
Thunderstorm at harvest													
S	≤ 1								SSSS	SSSS	SSSS	SSSS	SSSS
E & R	≤ 15	ERER	ERER				ERER	ERER	ERER	ERER	ERER	ERER	ERER
Best planting option													
Soybean		1	2						4	3			
Sweet potato		2	1	3	4								
Rice		2	1				4	3					

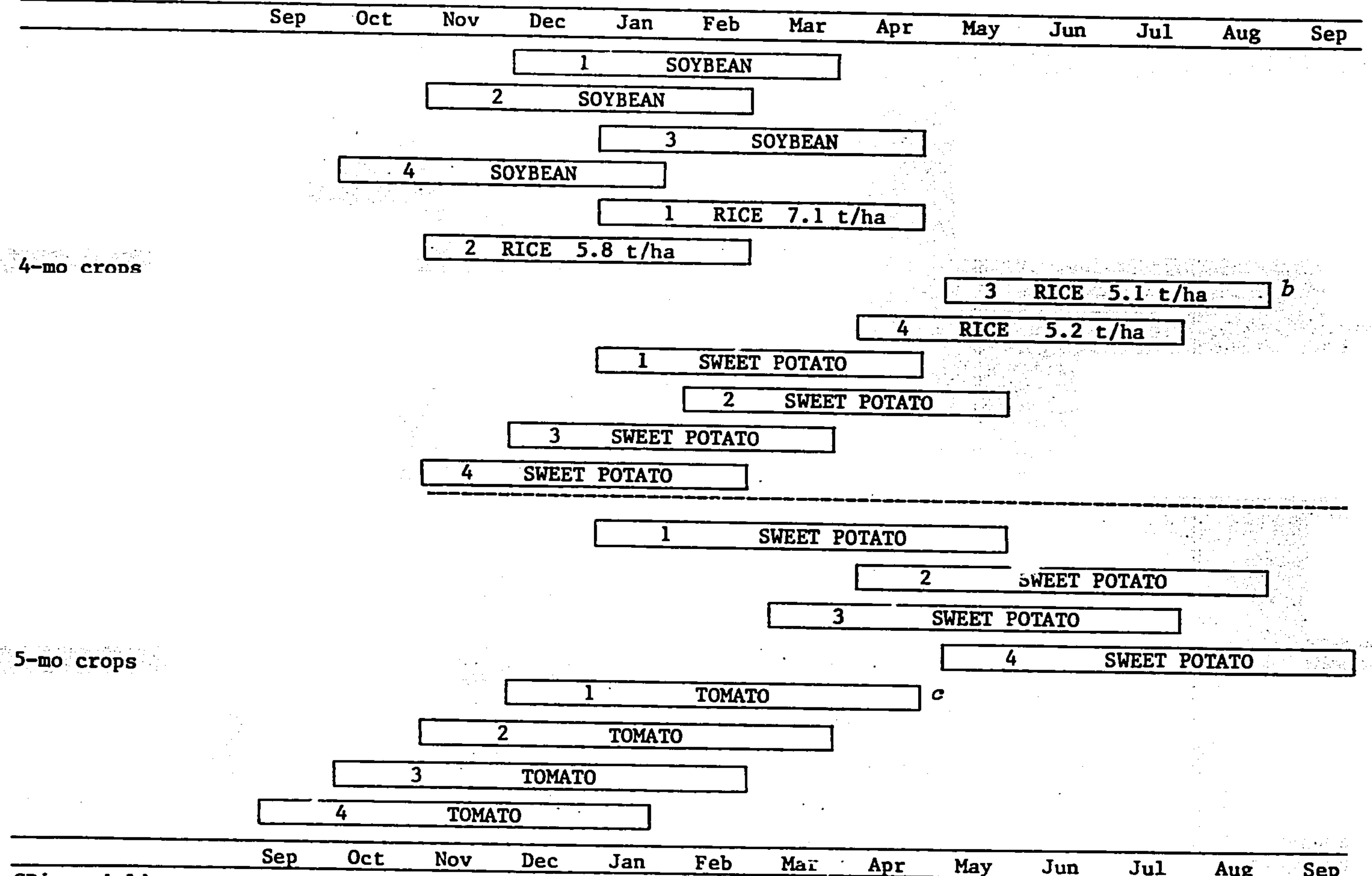
[a]S = soybean, E = sweet potato, R = rice, X applies to all crops. Source: Tables 3 & 7.

Table 10. Optimal cropping periods for Chinese cabbage, white potato, and mung bean, based on evaluation of environmental conditions. Los Baños, Laguna, Philippines.[a]



[a]Capital letters indicate heat-tolerant lines. No heat-sensitive Chinese cabbage or white potato lines (lowercase letters) were suitable for planting in Los Baños. Source: Table 8 and similar tables for 2-mo crops of Chinese cabbage and 3-mo crops of Chinese cabbage and white potato. Crops are ranked by best planting option.

Table 11. Optimal cropping periods for soybean, rice,[a] sweet potato, and tomato, based on evaluation of environmental conditions. Los Baños, Laguna, Philippines.

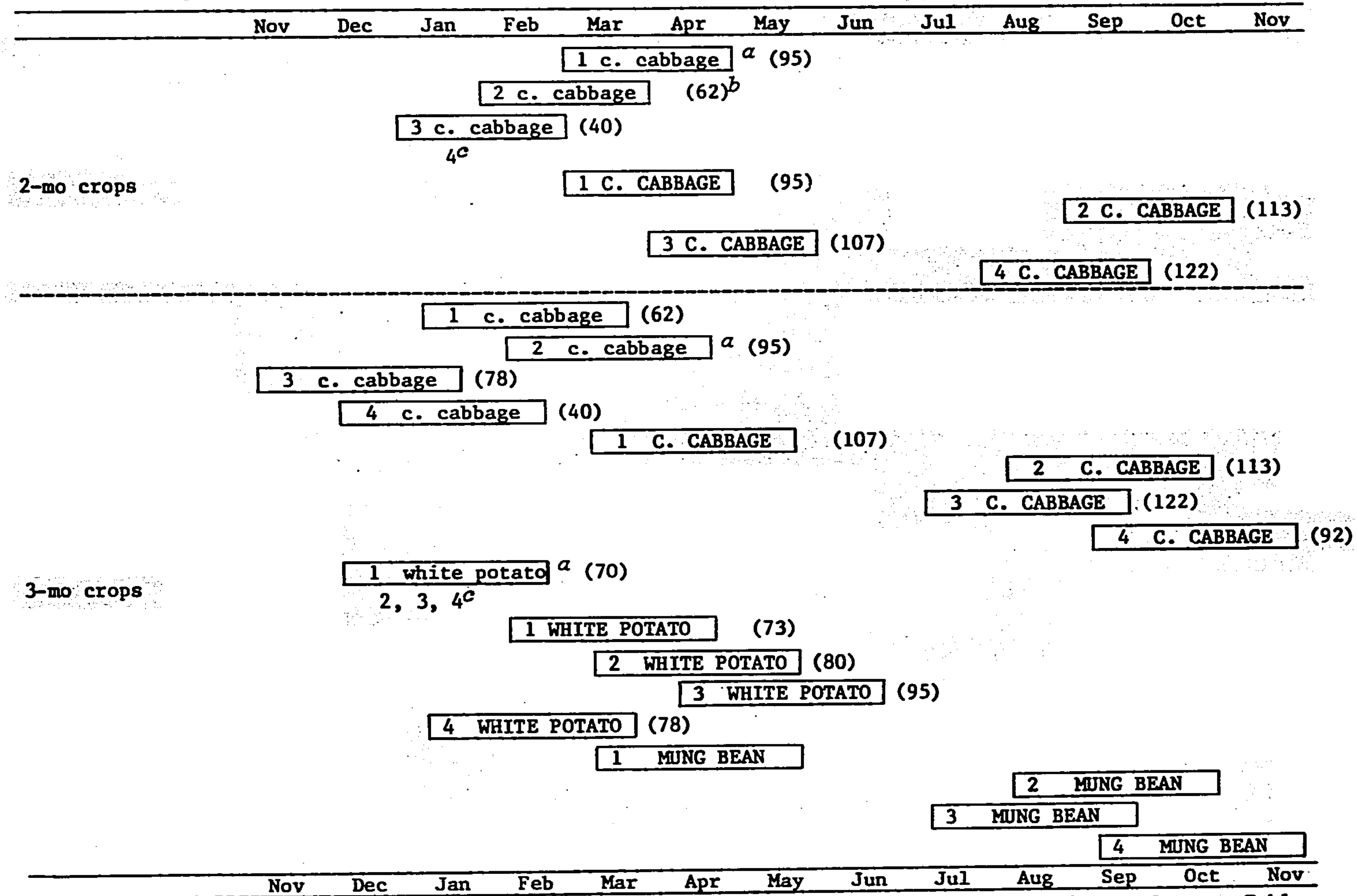


[a]Rice yields are av monthly values for IR747-82-6, which was planted every 2 weeks at IRRI (yield range: 7.1-4.2 t/ha) (Yoshida & Parao 1976).

[b]Damaged by insect pests. Source: Yoshida & Parao 1976.

[c]Heat-tolerant lines indicated by all caps. No heat-sensitive tomato lines (lowercase letters) were suitable for planting in Los Baños. Source: Tables similar to Table 8 for 4-mo crops of soybean, rice, and sweet potato, and 5-mo crops of sweet potato and tomato. Crops are ranked by best planting option.

Table 12. Optimal cropping periods for Chinese cabbage, white potato, and mung bean based on evaluation of environmental parameters. Kaohsiung, Taiwan, Republic of China.[a]

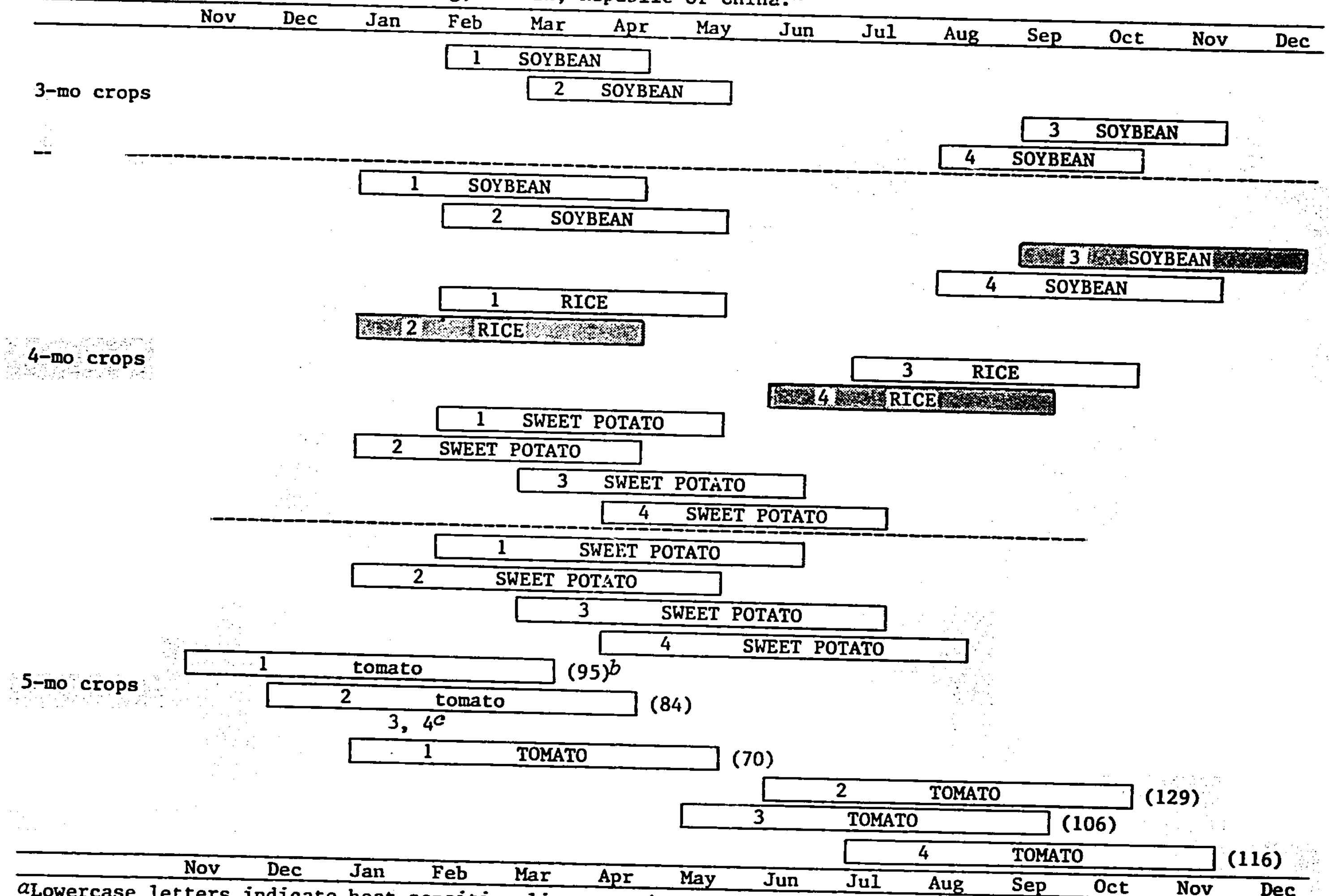


[a]Lowercase letters denote heat-sensitive lines. Capital letters denote heat-tolerant lines. Source: Tables similar to Table 9 for 2-mo crop of Chinese cabbage and 3-mo crops of Chinese cabbage, white potato, and mung bean. Crops are ranked by best planting option.

[b]The numbers in parentheses are Taiwan price indices for harvest month(s) (Taiwan 1972-76, Huang & Calkins 1978).

[c]Other cropping options cannot be determined.

Table 13. Optimal cropping periods for soybean, rice, sweet potato, and tomato, based on evaluation of environmental parameters. Kaohsiung, Taiwan, Republic of China.[a]



[a]Lowercase letters indicate heat-sensitive lines, capital letters indicate heat-tolerant lines. Source: Table 9 and similar tables for 3-mo crop of soybean and 5-mo crops of sweet potato and tomato. Shading indicates the cropping sequence that most closely approximates the actual planting cycle most frequently used in Kaohsiung area (Liu et al 1978). [b]The numbers in parentheses are Taiwan mean price indices for harvest months (Taiwan 1972-76, Huang & Calkins 1978). [c]Other cropping options cannot be determined.

Table 14. Comparison of harvest month(s) price indices for optimal cropping periods of heat-sensitive and heat-tolerant tomato, Chinese cabbage, and white potato. Kaohsiung, Taiwan.

Rank of cropping option	Price indices							
	Chinese cabbage (2 mo)		Chinese cabbage (3 mo)		White potato (3 mo)		Tomato (5 mo)	
	HS	HT	HS	HT	HS	HT	HS	HT
1	95	95	62	107	70	73	95	70
2	62	113	95	113	-	80	84	129
3	40	107	78	122	-	95	-	106
4	-	122	40	92	-	78	-	116
Mean	65.7	109.2	68.8	108.5	70	81.5	89.5	105.2

a/ HS = heat-sensitive plant types, HT = heat-tolerant plant types. Source: Taiwan 1972-1976, Huang & Calkins 1978.

help evaluate the merits of a given cropping pattern, such as seasonal price indices of crops with a high seasonally specific price variability (Tables 12 and 13), dominant cropping patterns (Table 13), or yield of crops harvested in indicated months (Table 11).

DISCUSSION

This analytical method enables one to identify potentially productive cropping periods even with limited environmental data. The variables and crops included depend upon the environment and the data available. If possible, socioeconomic factors should be integrated into the analyses.

Vegetable crops generally fit well into rice-based cropping systems but their roles vary with species, genotype, location, and environment. Heat tolerant tomato, Chinese cabbage, and white potato cultivars fill definite voids in the cropping sequence in Kaohsiung and, judging from the comparative price indices (Table 14), should increase farmer incomes. In Los Baños these vegetables provide an opportunity for more crop diversification from September through February (planting months). Rice and sweet potato are the only crops which can be planted in March and April. None of the crops included in this example are suitable for planting in July or August in Los Baños. The present analysis suggests a gap in the Los Baños cropping system. Other crops should be examined to identify suitable candidates to fill the void in some months and increase diversity in others.

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Climate change in India

R. E. Huke and S. Sardido

Premises concerning recent climatic change in India have been advanced. Data for 11 stations widely scattered all over the country were examined in detail. Evidence shows that rainfall in the decades since 1930 has been highly favorable for rice production. Other data indicate a significant increase in weather variability since the early 1940s. Clearly some climate change is under way and should be studied carefully.

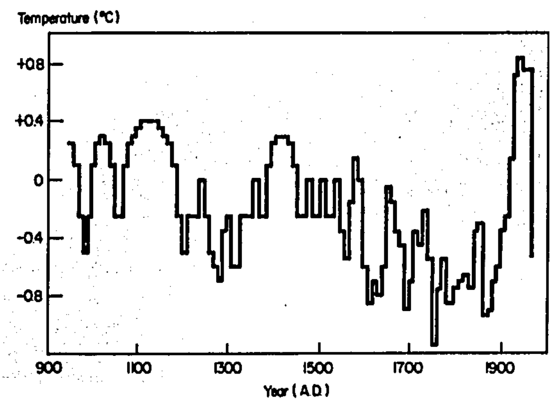
In the past decade a wide range of theses concerning the direction and magnitude of climate change has been presented. Any change, whether large or small and in any direction, would have major implications for the future of farming, especially in regard to the production of rainfed rice and to multiple cropping based on rice. This paper aims to investigate whether or not there has been a climatic perturbation in India in the past century.

Bergthorsson (1962) presented a reconstruction of Iceland's decadal mean annual temperatures for the past millenium. His diagram (Fig. 1) indicates that in the past 1,000 years, Iceland experienced the warmest temperatures in the period 1930 to 1960. Readings during that 30-year period were as much as 1.6°C above those of the last third of the nineteenth century.

Bryson (1975) suggests that as temperatures in the higher latitudes of the northern hemisphere increase, the subtropical anticyclones move northward and the monsoon rains penetrate further into India. He postulates that, "... during those times in earth history that are more summerlike, the monsoons will be better and that during more winterlike times ... (there will be) ... less monsoon rainfall."

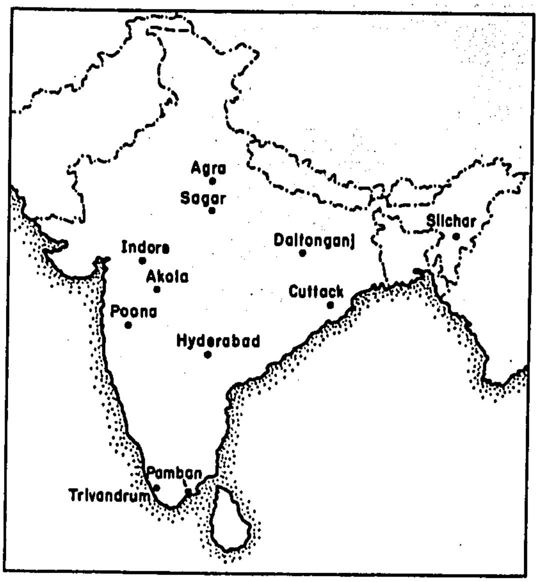
If Bergthorsson's temperature model and Bryson's hypothesis are accepted, it follows that a shift in India's rainfall should be in evidence from an analysis of historic data.

Any large shift in either the volume or in the temporal or spatial distribution of rainfall in India would be crucial for that nation's rice production. Of the 38.4 million ha of rice planted annually, 60% is rainfed and subject to periodic droughts. A decrease in India's rainfall would lead to a shorter and less reliable period during which soil moisture levels remain at saturation; thus moisture stress may reduce rice and other grain crop yields. Barker and Herdt (1979) make a case for emphasizing research on rainfed rice. O'Toole and Chang (1978) discuss the problems of rice production in drought-



1. Chart of temperature change in Iceland (Bergthorsson 1962).

International Rice Research Institute, P.O. Box 933, Manila, Philippines.



2. Location of 11 stations in India for which data are reviewed.

prone environments. However, if the moisture change in India were toward increased precipitation, yields might show greater stability and perhaps some increase.

Whether world temperatures are increasing or decreasing, and whether whatever change is taking place is the result of man's impact on the climate or is a manifestation of natural cycles are subjects open to considerable debate. Climatologists, however, appear to be unified on the subject of variability. Variability appears to be increasing. The recent literature has many titles such as *Climate outlook: variable and possibly cooler* (Lansford); *Unsettled and variable climate - uncertain food supply* (Decker); *Climatic change: are we on the brink of a pronounced global warming?* (Broecker); and *Global cooling?* (Damon).

Bryson and Murray (1977) argue that temperatures in the northern hemisphere have been cooling off rapidly, although not regularly, since 1950; and that an analysis of past climate indicates greater weather variability on a weekly, monthly, and even an annual basis during such cooling periods.

If this argument is valid, it might be possible to identify increasing variability in the data from India for the years since 1950.

Eleven well-dispersed stations with long and continuous records of precipitation and temperature were chosen for analysis (Fig. 2). In all cases, except for Trivandrum, the records are continuous with no missing years and no sharp breaks due to changes in exposure, location, or instrumentation. At Trivandrum, recording of rainfall data started in 1853 but because the records were incomplete, only data from 1890 through 1960 were used. Although the elevation of the rain gauge at the station was changed by 4 m in September 1931, no significant shift in the recorded rainfall was discovered and the station data were retained in the study.

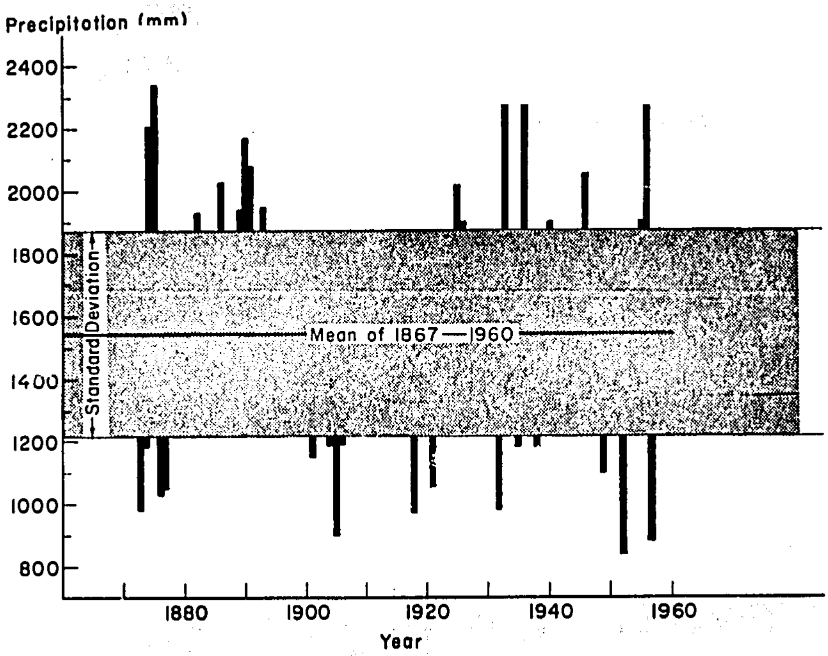
For each station, 10-year running means for temperature and precipitation were developed and graphed. The graphs emphasized the great variability of rainfall from year to year and the relative stability of the temperature record despite the damping effect of the means.

Tables and graphs were developed from the long-term means for each station to show the dates and the extent of precipitation and temperature variability. Because all years differ to some degree from the norm, only those with variability greater than one standard deviation were graphed. Examples portraying the climatic history of Cuttack are shown as Figures 3 and 4. No dramatic change is evident.

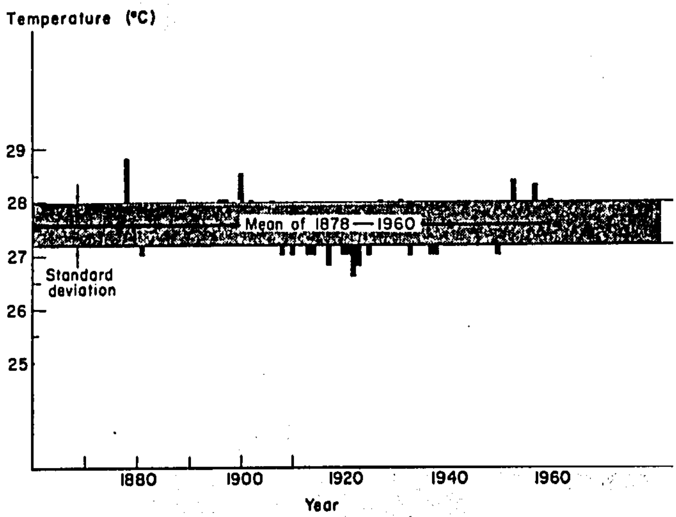
The temperature and precipitation records were divided at 1930, the year that marked the beginning of Iceland's very warm period as defined by Bergthorsson. The pre-1930 data were compared with the post-1930 data for each station.

Results of the analysis of precipitation are shown in Table 1. Nine stations showed a rainfall increase after 1930, and 4 showed an increase large enough to be significant at the 5% level. Most importantly, the four stations showing a significant increase--Agra, Akola, Indore, and Sagar--are close to the humid-subhumid boundary where even small increases in moisture are likely to be very important for increasing crop productivity. The two stations showing moisture decreases were in central and southern India.

Results of the temperature analysis were far more varied than those of rainfall (Table 2). Of the 11 stations, 6 showed an average increase of 0.3°C in mean temperature; Trivandrum jumped by 0.8°C; and the 4 remaining stations showed declines of 0.5°C or less. In 5 cases, the changes were significant at the 5% level, but no trend was clear



3. Precipitation variability. Cuttack, India.



4. Temperature variability. Cuttack, India.

as 3 of the changes were positive and 2 were negative.

The temperature changes had no recognizable spatial pattern and neither paralleled nor were inversely related to the changes in rainfall. For example, both Agra and Sagar showed significant increases in rainfall. Agra, as expected, showed a temperature decrease of 0.54°C, significant at the 5% level. But Sagar, which had a considerably greater net increase in rainfall, actually showed a modest, although insignificant, increase in temperature as well.

A simple linear correlation between temperature change and precipitation change for the 11 stations gave an *r*-value of .324, far lower than the figure needed for significance at the 5% level. Contrary to expectations, the figure suggests a very low positive relationship between the two variables.

The data for the 11 stations do not appear to strongly support the conclusion

Table 1. Precipitation change in selected Indian locations.

Station	Start of record	Mean (mm) Pre-1930	Mean (mm) Post-1930	Change[a/] (mm)
Agra	1862	680	768	↑ 88*
Akola	1870	776	877	↑101*
Cuttack	1867	1530	1568	↑ 38^{ns}
Daltonganj	1893	1155	1235	↑ 80^{ns}
Hyderabad	1893	801	773	↓ 28^{ns}
Indore	1877	838	1035	↑197*
Pamban	1893	947	924	↓ 23^{ns}
Poona	1856	698	714	↑ 16^{ns}
Sagar	1870	1183	1394	↑211*
Silchar	1869	3221	3301	↑ 80^{ns}
Trivandrum	1890	1722	1836	↑114^{ns}

[a/]ns = not significant at 5% level. * = significant at 5% level.

Table 2. Temperature change in selected Indian locations.

Station	Start of record	Mean (°C) Pre-1930	Mean (°C) Post-1930	Change[a/] (°C)
Agra	1876	26.08	25.54	↓0.54*
Akola	1875	26.93	27.23	↑0.30*
Cuttack	1878	27.55	27.63	↑0.08^{ns}
Daltonganj	1893	25.22	25.53	↑0.31*
Hyderabad	1893	26.75	26.31	↓0.44*
Indore	1878	24.50	24.45	↓0.05^{ns}
Pamban	1891	28.18	28.07	↓0.11^{ns}
Poona	1876	25.05	25.12	↑0.07^{ns}
Sagar	1875	25.11	25.24	↑0.13^{ns}
Silchar	1870	24.83	24.94	↑0.11^{ns}
Trivandrum	1890	26.33	27.12	↑0.79*

[a/]ns = not significant at 5% level. * = significant at 5% level.

of Bryson and Murray (1977): "Our evidence indicates that since A.D. 1700 all 30-year periods (in the northern hemisphere as a whole) have been colder than the 1931-1960 period."

We assumed that at any given station the variability of soil moisture balance most strongly influences rainfed rice yields. We looked at this balance in Cuttack. Cuttack lies in the heart of a major rice area at the head of the delta of the Mahanadi River and in a district where about half of the rice is unirrigated. The records for Cuttack provide temperature and rainfall data dating from 1878.

A computer program based on Thornthwaite (1955) formulas for potential evapotranspiration (PE), soil moisture storage, actual evapotranspiration, and water deficit was used to process the data for each of the 83 years from 1878 through 1960. Temperature records for the individual years from 1867 through 1877 were not available; for that period the program used the pre-1930 temperature mean and the rainfall records for the individual years.

The "normal" data indicate that for the 5-month period from June through October the mean monthly precipitation exceeds the PE in every month, soil moisture is at full capacity for the entire period, and some runoff takes place each month (Table 3). Unfortunately for the farmer there is seldom if ever a year during which actual field conditions parallel "normal" conditions.

The record shows that July, August, and September were the least drought-prone months at Cuttack. Over the 94-year period PE exceeded actual precipita-

Table 3. Years between 1867-1960 in which actual precipitation < potential evapotranspiration in the wet season, by month. Cuttack, Orissa, India.

	Jun		Jul	Aug	Sep	Oct	
	1869	1923	1893	1869	1889	1867	1908
	1870	1924	1898	1871	1894	1868	1909
	1871	1926	1904	1877	1899	1869	1911
	1873	1927	1907	1892	1901	1871	1914
	1876	1929	1911	1894	1902	1873	1918
	1877	1931	1915	1899	1916	1876	1919
	1879	1932	1916	1905	1918	1877	1920
	1882	1935	1918	1932	1919	1878	1921
	1885	1939	1949	1935	1938	1879	1922
	1888	1942	1955		1947	1880	1924
	1891	1945			1953	1881	1927
	1893	1948			1957	1883	1930
	1898	1949				1884	1932
	1900	1951				1885	1933
	1901	1953				1887	1934
	1905	1955				1888	1935
	1913	1957				1891	1937
	1920	1958				1893	1940
		1959				1894	1942
						1895	1943
						1896	1947
						1901	1948
						1902	1950
						1904	1951
						1905	1953
						1906	1957
						1907	1960
Total no. of occurrences	37		10	9	12	54	
Mean PE (mm)	187		168	174	165	147	
Mean precip. (mm)	207		355	365	252	168	

tion during these 3 core months of the monsoon rainy season on only 10, 9, and 12 dates, respectively. For 4 of the 12 years when September was dry, either July or August was also dry. In 1894 and 1899, both August and September were dry and famine prevailed in Orissa. In 1916, July and September together had 383 mm less than "normal" rainfall. In 1918, the deficit for those 2 months was slightly over 400 mm and the 2-month total was the lowest in 94 years of rainfall records. This disastrous season ended with only 3 mm of precipitation in October rather than the "normal" 168 mm. Records show that 1918 was one of the most serious famine years in the history of Orissa.

The data suggest that a dry month early in the core of the rainy season is frequently followed by another dry month later in the same year. Such a sequence spells disaster to the farmer on non-irrigated land. This phenomenon should be investigated further with a view toward developing cropping systems designed to minimize losses.

Table 3 indicates that June and October have almost identical surpluses of precipitation over PE. Under such conditions, these months may show roughly equal frequencies of drought. However, the record shows that June suffered from drought 37 times while October was hit on 54 occasions. Perhaps this indicates that in eastern India, at least, the early portion of the monsoon is more reliable than the latter. Again the data suggest that changes in the cropping calendar might lessen potential losses due to drought in October.

In Table 3, the dates from the 1950s appeared more frequently than did dates

Table 4. Examples of Thornthwaite data on water balance for Cuttack, Orissa, India. (Values are in mm)

1880
a typical year

PRECIP.	POTENTIAL EVAPO.	SOIL STORAGE	WATER DEFICIT	ACTUAL EVAPO.
1	67	15	52	15
53	98	10	39	58
0	161	2	153	8
34	183	0	148	36
170	191	0	21	170
203	181	23	0	181
278	179	100	0	179
538	174	100	0	174
261	150	100	0	150
131	147	85	1	146
35	86	52	17	69
0	57	29	35	22

TOTAL WATER DEFICIT = 464.5646

1956
wettest year of record

PRECIP.	POTENTIAL EVAPO.	SOIL STORAGE	WATER DEFICIT	ACTUAL EVAPO.
0	78	13	62	16
59	83	11	21	62
3	167	2	155	11
1	186	0	184	3
157	197	0	40	157
465	164	100	0	164
345	168	100	0	168
521	174	100	0	174
445	159	100	0	159
349	138	100	0	138
27	85	56	14	71
0	66	29	39	27

TOTAL WATER DEFICIT = 515.3125

1957
dryest year of record

PRECIP.	POTENTIAL EVAPO.	SOIL STORAGE	WATER DEFICIT	ACTUAL EVAPO.
12	84	2	70	14
20	96	1	75	21
8	151	0	143	9
1	183	0	182	1
3	208	0	205	3
101	198	0	97	101
246	179	67	0	179
337	174	100	0	174
146	159	88	1	158
10	156	20	79	77
0	99	8	86	13
0	74	4	70	4

TOTAL WATER DEFICIT = 1006.3634

from any other 10-year period. In 1956, Cuttack had the highest rainfall total in the 94 years of record, and in 1957, it had the lowest total ever recorded. The water balance data for these years and for 1880, a year quite close to "normal", are shown in Table 4.

A count was made for each station recording the date and the actual level of rainfall or temperature whenever that record varied from the clino (long-term average, i.e. 94 years) by more than one standard deviation. A test of variability was made to compare decades (Table 5).

The 1950s show no significant

Table 5. Test of variability[a] (using *F*-test for variance ratios) of temperature and precipitation. Eleven stations in Cuttack, Orissa, India.

Year	S^2	DF	S_1^2/S_j^2	S_2^2/S_j^2	S_3^2/S_j^2	S_4^2/S_j^2	S_5^2/S_j^2
1951-60	440,365.4	83					
			1.05ns				
1941-50	418,166.76	50					
			1.89*	1.99**			
1931-40	830,080.28	66					
			2.43**	2.56**	1.29ns		
1921-30	1,069,038.21	66					
			1.65*	1.74*	1.140ns	1.47ns	
1911-20	728,231.79	72					
			1.51ns	1.60*	1.24ns	1.60*	1.09ns
1901-10	667,402.99	54					

[a] * = significant. ** = highly significant. ns = not significant. This is the two-tailed version of the *F*-test. In the *F*-ratio S_1^2 is always the larger of the two mean squares.

Table 6. Comparison of sample mean and population mean. Deviations greater than one standard deviation from "clino".

Dates	Total observations	Readings > 1_s from mean		z [a]
		Number	%	
1951-60	220	84	38.2	15.56**
1941-50	220	51	23.2	2.90**
1931-40	220	67	30.4	[illegible]76ns
1921-30	220	67	30.4	0.75ns
1911-20	220	69	31.4	2.66**
1901-10	220	55	25.0	-9.48**
Total	1320	393	30.0	

[a] ns = not significant. ** = highly significant.

increase in variability compared to the 1940s, but either decade or especially both of them together differ significantly from all other decades in the twentieth century. The 11 stations showed a marked change in the weather variability in the decades following 1940 when compared to that of earlier periods. The contrast with the first 10 years of the century is least strong.

For a different perspective, a test to compare sample mean with population mean was carried out. The percentage of total observations for each decade, which were more than one standard deviation removed from the clino, were compared with the mean for the entire record (Table 6).

The 1950s is a period of greatly increased weather variability. In contrast, at the turn of the century and in the 1940s, the weather showed a significant decrease in variability. The record could be read as suggesting that from the latter part of the teens through the 1920s and 1930s, weather in India showed typical annual variability. During the 1940s a year-to-year similarity in the weather was unmatched since 1900, but during the 1950s the tranquility was shattered by a variability greater than that for any other decade of the century. This finding is consistent with the theories of climate change.

CONCLUSIONS

Data from 11 stations well dispersed over India suggest some climate change in recent decades. Annual rainfall totals have increased in broad areas of North-Central India after 1930, and the annual variability in yearly rainfall and temperature has increased markedly since 1950.

If it develops that the Bryson-Murray thesis postulating a northern hemisphere cooling is correct, then the result in India should be a marked reversal in this trend toward increased rainfall. The increasing tempo of variability is already manifest. If this is followed by a decline in rainfall, the result could spell disaster for rainfed rice yields in India.

It appears that the benign climate of the late 1930s and the 1940s has started to change. Whether this change will be for the better or for the worse is not yet clear. It is clear, however, that in a period when population numbers and the demand for food are exerting extraordinary pressures on the environmental resources, any change in those resources will have vast repercussions on the economic well-being of the nation. The question of climate change in India - its potential magnitude and direction - is a topic worthy of increased scientific study.

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Maximum water requirement of upland rice variety OS6 in the humid/subhumid zone of West Africa

T. L. Lawson and K. Alluri

Drainage lysimeters were used to study the pattern and amount of moisture consumption of OS6, a typical dryland rice variety, in the humid to subhumid transition zone of West Africa. Between 538 mm and 622 mm water was required depending on soil type and crop growth. The water use efficiency with respect to total dry matter was virtually the same for the two soils used: Iwo and Alagba, both Oxic Paleustalfs. Grain yield per unit of water used in maximum evapotranspiration was, however, better on the Iwo soil (67.56 kg/ha per cm) than on the Alagba (60.93 kg/ha per cm).

Four phases were identified in the pattern of moisture use: an initial phase of low moisture consumption with maximum evapotranspiration (ETm) to Class A pan evaporation ratio of 0.7-0.75, a rapid increase in ETm paralleling an increase in leaf area and tillering, a much longer phase of high water consumption, and a declining ETm following peak values of 3-4 weeks before maturity.

Matching this moisture consumption pattern to rainfall distribution should be a logical way of selecting areas for rice production.

Rice, more than any other major food crop, has critical requirements for high and regular water availability. The water required for a given site is the total lost through evapotranspiration, seepage, and percolation, since very little is actually retained by the plant. High temperatures and solar radiation increase evapotranspiration and water requirements but favor growth and yield. Rice's semi-aquatic nature and shallow roots limit the soil volume that can be exploited and contribute to the higher water requirement compared to that of upland cereals with deeper roots, such as maize, sorghum, and millet. Because high rice yields can be obtained in flooded lowlands, much of the world's rice is produced under systems with good water control. However, more land with well-drained soils is being brought into the production of rice that must depend entirely on the rainfall that these soils can hold. Knowledge of the pattern and magnitude of dryland rice's moisture demand constitutes a fundamental parameter in determining the suitability of an environment for production.

The cropping season of the humid or subhumid zone of West Africa experiences variable rainfall and attendant dry spells. The soils are shallow and their poor physical character contributes to low water-holding capacity.

The objective of this study is to determine the maximum evapotranspiration of OS6, a typical dryland rice variety (in Nigeria), as the equivalent of a crop's evaporative demand under prevailing weather conditions. The evaporative demand is a relatively conservative property and the results are expected to reflect the average condition for the region's main cropping period.

MATERIALS AND METHODS

Site

The experiment was conducted at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria (07°31'N, 03°54'E, alt 220 m). As part of the transitional belt between the humid and subhumid regions of West Africa, the rainfall distribution in the area is typically bimodal with a distinct break in the growing season occurring in August.

International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

Table 1. Some physicochemical characteristics of Iwo and Alagba soil series (Oxic Paleustalfs).[a]

Depth	Texture	Bulk density	Moisture (%) 0 bar	0.3 bar	1.5 bars	N(%)	C(%)	CEC
			IWO SOIL					
0 - 12 cm	sandy loam	1.35	49.0	18.1	12.7	0.22	2.08	10.79
13 - 20 cm	sandy clay loam	1.61	33.6	11.8	8.4	0.09	0.77	5.38
21 - 42 cm	sandy clay loam	1.64	37.4	17.2	13.0	0.07	0.58	4.79
			ALAGBA SOIL					
0 - 13 cm	sandy loam	1.24	41.0	13.2	10.0	0.16	1.56	9.04
14 - 30 cm	sandy loam	1.46	31.8	7.4	5.9	0.06	0.70	2.90
31 - 45 cm	sandy clay loam	1.57	38.6	12.9	6.7	0.05	0.44	2.83

[a]After personal communications with F. R. Moormann, A. S. R. Juo, R. Lal., IITA.

The first season (late March to July) starts at a time of high evaporative demand -- high insolation, high temperatures, and high vapor pressure deficits, all of which decrease as the season progresses. The second season (mid-August to October) starts with overcast conditions. The evaporative demand and the related factors increase as the season runs its course and decrease again thereafter. Thus, the weather trends completely reverse during these two seasons.

Lysimeters

The two lysimeters used in the experiment consist of steel tanks, 3.2 mm thick, 256 cm in diameter, and 110 cm deep (Lawson 1977). Buried up to 5 cm from the top, they were filled to ground level with a reconstitution of two representative soil profiles, one from an Alagba series and the other from an Iwo series. Both soils are classified as Oxic Paleustalfs, but the latter has a higher clay content, more gravel in the subsurface horizon, and a higher cation exchange capacity (Table 1). The bottom 25 cm was filled by stone overlaid with sand to facilitate drainage. A constant water level was maintained at 80 cm below the soil surface. Both lysimeters had been planted to several crops in previous seasons, after an initial settling period under grass, mainly *Panicum maximum*.

Cropping

The land surrounding the lysimeters was plowed, harrowed, and leveled. The soils in the tanks were similarly treated with hand implements. Ammonium sulfate at 20 kg N/ha was applied before planting and 4 and 6 weeks after planting (WAP).

Variety OS6 was sown on 18-19 October 1978 and planting density was 22 hills/m^2 after thinning. The 25 x 30 m of cropped area around each lysimeter provided a reasonable fetch.[1] There was a field of cowpea downwind from the rice plots. The upwind area was planted with soybean with the agroclimatological station on an adjacent grassed area. The site of the Alagba soil lysimeter was fully instrumented and the measurements will not be reported here.

Determination of maximum evapotranspiration

The maximum water use by the crop growing on the lysimeters was determined for a given period by the water balance equation:

$$P + I = ETm + D + AW$$

where, P = precipitation
I = irrigation water added
ETm = maximum evapotranspiration
D = drainage
AW = change in water storage.

By taking measurements at the end of each drainage period, the change in water

[1]Fetch – wide, homogenous surface area upwind from the lysimeter.

storage is reduced to zero (Eldin et al 1969, Tanner 1967). Additional water was added to the lysimeter daily and early in the morning after the drainage measurements. The amount added was estimated from the preceding day's evaporation and increased by a fraction to effect drainage (Lawson 1977). Any rainfall or sprinkler irrigation between measurements was carefully monitored by a series of rain gauges and taken into account in adding water. A condition of nonlimiting soil moisture was thus maintained at all times so that deducting the amount of water drained from the total water added gave the water used by the crop, i.e. its maximum evapotranspiration.

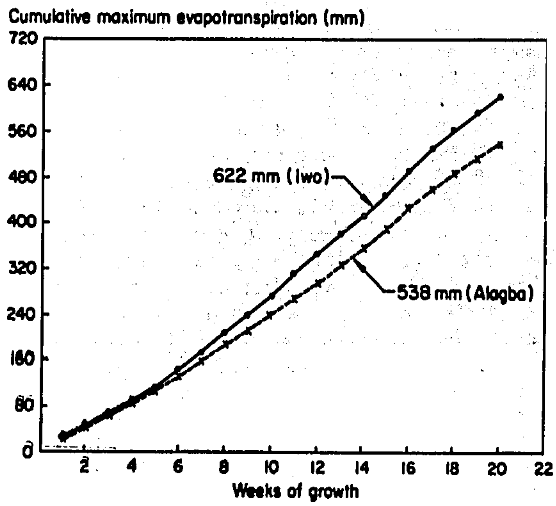
RESULTS AND DISCUSSION

Maximum evapotranspiration and crop growth

The weekly mean and cumulative values of maximum evapotranspiration together with other relevant parameters on the prevailing weather are given in Table 2 and Figure 1.

The water used by the crop remained stable at about 3 mm/day during the first 4 weeks of growth. There was a sharp increase between the 4th and 8th weeks when values reached an average of about 4.8 mm/day and 4 mm/day for the Iwo and Alagba soils. These higher levels were maintained with some fluctuations up to the 16th week when peak values of 6.14 mm/day and 5.11 mm/day were reached. There was a continuous decline thereafter.

Water use paralleled crop development. The contribution of transpiration



1. Cumulative maximum evapotranspiration in rice variety OS6.

Table 2. Weekly mean values of solar radiation (Ra), saturation vapor pressure deficit (Ae), wind speed at 2 m (V), pan evaporation (Eo), and maximum evapotranspiration (ETm) for two soil types.

Week	Period (1978-79)	Ra (cal/cm^2 per day)	Ae (mb)	V (kmph)	Eo (mm)	Iwo ETm (mm)	Alagba ETm (mm)
1	20/10 - 26/10	443.3	6.96	4.0	4.48	3.28	3.05
2	27/10 - 21/11	460.2	5.98	3.5	4.06	3.19	2.94
3	3/11 - 9/11	411.4	6.84	3.0	4.06	3.08	2.89
4	10/11 - 16/11	493.7	8.95	2.4	3.93	2.88	2.85
5	17/11 - 23/11	496.1	10.36	2.9	4.21	3.45	3.47
6	24/11 - 30/11	447.7	10.02	2.9	3.98	4.55	3.47
7	1/12 - 7/12	445.3	10.65	3.4	4.11	4.55	4.11
8	8/12 - 14/12	396.9	9.30	2.9	3.69	5.16	4.02
9	15/12 - 21/12	377.5	8.19	2.9	3.24	4.10	3.54
10	22/12 - 28/12	416.3	11.09	4.3	4.27	4.89	3.70
11	29/12 - 4/1	392.1	10.20	9.3	3.70	5.42	4.13
12	5/1 - 11/1	355.8	6.06	3.2	3.21	5.02	3.98
13	12/1 - 18/1	346.1	9.71	3.7	3.75	4.64	4.49
14	19/1 - 25/1	367.9	12.10	3.4	3.96	4.65	4.23
15	26/1 - 1/2	445.3	13.86	4.8	5.74	5.40	4.77
16	2/2 - 8/2	493.7	15.17	5.1	6.15	6.14	5.11
17	9/2 - 15/2	469.5	14.77	5.1	5.86	5.35	4.56
18	16/2 - 22/2	452.6	13.20	4.8	5.87	4.41	4.20
19	23/2 - 1/3	474.4	14.84	5.0	6.28	4.55	3.91
20	1/3 - 8/3	486.5	13.62	4.6	6.14	4.19	3.23

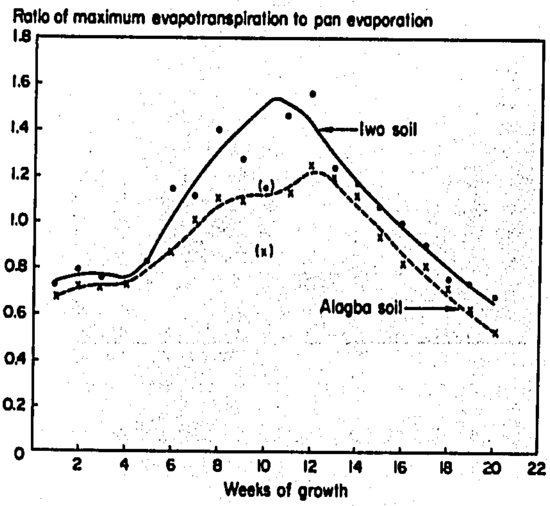
to evapotranspiration during the first 4 weeks was minimal because of the limited leaf area at this stage; water use was therefore mainly evaporation from the soil surface. The upsurge in evapotranspiration during the 5th and 6th weeks was associated with the development of tillers and a rapid increase in leaf area. A more luxuriant growth generally followed the second application of fertilizer late in the 4th week. Evaporative demand also increased (Table 2) and contributed slightly to the increase in water use. The peak values for expotranspiration coincided with the flowering stage.

The decline in water use in the 9th week reflects reduced evapotranspiration in rice associated with the period just before heading (Angladette 1966, Dupriez 1964), reinforced in this case by the prevailing weather conditions. The peak maximum evapotranspiration in the 16th week also reflects a similar morphophysiologically based phenomenon reinforced by conditions of high evaporative demand.

Cumulative maximum evapotranspiration amounted to 622 mm and 538 mm for the crops on the Iwo and the Alagba soils, giving a mean daily value of 4.44 mm in the former and 3.89 mm in the latter. These compare with the value of 4 mm reported by IRRI (1965). The disparity is attributable to growth differences on the two soils (Table 3). The Iwo soil, with inherently better chemical properties, supported much more vigorous growth, and plants with higher total dry matter production and better grain yield. Similar differences have been observed in cowpea on these soils (Lawson 1977).

Water use efficiency

Water use efficiency with respect to total dry matter was 148.0 kg and 148.9 kg/ha per cm on the Alagba and the Iwo soils. The crop grown on Iwo soil yielded 67.56 kg grain/ha per cm water -- 11% higher than the 60.93 kg/ha per cm on Alagba soil. This agrees with observations by Viets (1966) and Pendleton (1965).



2. Ratio of weekly mean maximum evapotranspiration in rice to class A pan evaporation.

Maximum evapotranspiration-pan evaporation ratio

The maximum evapotranspiration-pan evaporation ratio (Fig.2) followed a predictable pattern but varied more for the Iwo soil between the 6th and 12th weeks. The ratio averaged about 0.70 for Alagba soil and 0.75 for the Iwo soil in the first 4 weeks, increased to a mean maximum of about 1.15 and 1.40, and fell to absolute minimum values of 0.52 and 0.68 at the end of the season. The mean ratios over the season were 0.98 for the Iwo soil and 0.85 for the Alagba.

The early and late season values are lower than those obtained at Mvuazi,

Table 3. Crop parameters and yield figures for OS6 grown on Iwo and Alagba soils with nonlimiting soil moisture.

Parameter	SOIL TYPE Alagba	Iwo
Mean plant ht (cm)[a]	155.0	162.0
Mean tiller number per plant[a]	7	10
Total dry wt (kg/ha)	7964	9262
Total grain wt (kg/ha)	3278	4204
1000-grain wt (g)	33.1	33.0

[a]Av of samples taken on 5 and 16 February 1979.

Zaire (Dupriez 1964), but the midseason values are comparable (Alagba soil) or higher (Iwo soil). The seasonal mean values -- 0.9 for Alagba and about 1.0 for Iwo -- in the present study are comparable to those of Mvuazi, which ranged from 1.00 to 1.14 over a 3-year period. They also compare to the values 1.04 and 1.03 obtained by Irithayaraj (1978) on two different rice varieties for the summer.

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V. Modeling and data analysis

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Climatic factors and the modeling of rice growth and yield

J. F. Angus and H. G. Zandstra

The application of crop models to rice research is reviewed. Among the rice-growing systems, rainfed wetland rice is an important type which is sensitive to weather variation and to which crop simulation models can be adapted. We describe a growth and development model for wetland rice that accounts for the effects of radiation, temperature, water supply, and nitrogen nutrition. Tests showed that the model quantitatively accounted for the yield interaction between radiation and nitrogen supply in a flooded environment, and qualitatively simulated the interaction of drought and nitrogen response in rainfed rice. However, the water balance and rice yield of a sloping field could not be accurately simulated because the contribution of lateral water flow was not considered. By looping the model's water balance so that lateral water outflow from one terraced field became the inflow to an adjacent field, a toposequence water balance model that gave improved soil water calculations was developed.

Deficiencies in the model are identified. A possible use of modeling in regional research is discussed.

This paper reviews the general types of crop models that have been and are being devised, discusses their usefulness for particular rice problems, and presents a simplified model of the growth and development of rainfed rice recently formulated at IRRI. The simplified model may be used for evaluating the adaptation of rainfed rice to climatic regions and studying the results of field experiments.

The virtues of simulation models in crop research have been argued previously (e.g. Nix 1976, de Wit 1978). Briefly, a model allows the synthesis and mobilization of existing knowledge about individual processes leading to yield and helps pinpoint deficiencies of knowledge. A model that works can calculate the crop's response to environmental changes. Passioura (1973) has argued that models should be simple, be readily testable in final yield and in subsystem calculations, and be amenable to improvement after experimental testing. Recent research (Wickham 1973; Ahuja 1974; Iwaki 1975; Paris and Price 1976; van Keulen 1976, 1978; papers in this conference) shows that rice problems can now be approached by modeling techniques.

Although much yield variation is due to weather, the effects of management, soil, and biotic factors must also be recognized. As a general strategy, the crop model should focus on factors responsible for most of the yield variations. Where nonweather factors are important, a model based solely on climate would be misleading. A model should address factors that can be manipulated by either the farmer or the breeder. This paper emphasizes the crop management-weather interaction leading to yield, and shows how simulation can increase our understanding of and ability to manage this interaction.

TYPES OF MODELS

Waggoner (1968) makes a distinction between strategic and tactical uses of weather data that can be applied to models. Strategic models are long-term oriented; tactical models, are for day-to-day decisions and assessment of currently growing crops. Tactical models are subdivided into those which forecast

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regional yields and those that assist the farmer in management activities.

Tactical models for yield forecasters

Crop production forecasts are made for grain storage, trade, speculation, and emergency food relief. Forecasting systems are well developed in several countries, such as in Canada where the wheat forecasting model is based on a simulation of water balance and phenology (Baier 1978), and in the USA where multivariate statistical models based on mean monthly weather data have been used (e.g. Thompson 1969).

The advantages of tactical models must be weighed against their costs. Their results also need to be evaluated against the next best alternatives. Certainly the effectiveness of simple reporting of crop condition by district advisers for rice forecasting systems should be assessed before a modeling procedure is adopted.

Tactical models for farmers

These models mostly forecast pest and disease damage in relation to weather. The forecast should be one which can be acted on (e.g. by spraying pesticides) and should be readily available to farmers, by radio broadcasts, for example.

Ideally, pest forecasts should be as available and effective for Asian rice farmers as they are for farmers elsewhere, but the basic environmental biology of many tropical rice pests is not well enough understood for this approach to be widely applied.

Strategic models

Rice farmers make most of their crop management decisions at sowing or shortly afterwards. The scope for tactical decisions is therefore limited and strategic decisions should be made on expectations of average future weather and an understanding of crop response to weather. Strategic models investigate the interaction between management and weather in a series of growing seasons.

Crop simulation is most usefully applied to rice production problems through use of strategic models. The stability and transferability of new rice technology have not been extensively tested. Crop simulation can help determine stability and transferability if an appropriate bank of weather data is available.

APPLYING MODELS TO RICE PROBLEMS

It is unlikely that a single modeling approach would be applicable to all rice systems (e.g. dryland and deepwater), and difficulties exist in applying to rice problems models devised for temperate crops. For example, the static regression approach, popular for forecasting regional yields of temperate crops on the basis of weather data, may not apply to rice. Although suitable weather data may be available, reliable long run regional yield estimates may be unavailable because production is difficult to estimate when most grain is consumed on the farm. Furthermore, recent changes in management practices and varieties may mean that weather effects are confounded with the rate of adoption of new systems, and with the different responses of new varieties to weather.

However, there are situations where models may be applied to rice without methodological problems. Rainfed wetland rice is an important cultural system (Barker and Herdt 1978) in which water stress commonly limits production (Morris and Zandstra 1978). The technique of water budgeting originally devised for dryland crops can be modified to apply to wetland conditions -- this is the core of the model that we describe. We include the effects of radiation, moisture and temperature, and attempt to account for the effects of nitrogen nutrition on plant growth.

A MODEL OF RICE GROWTH AND DEVELOPMENT

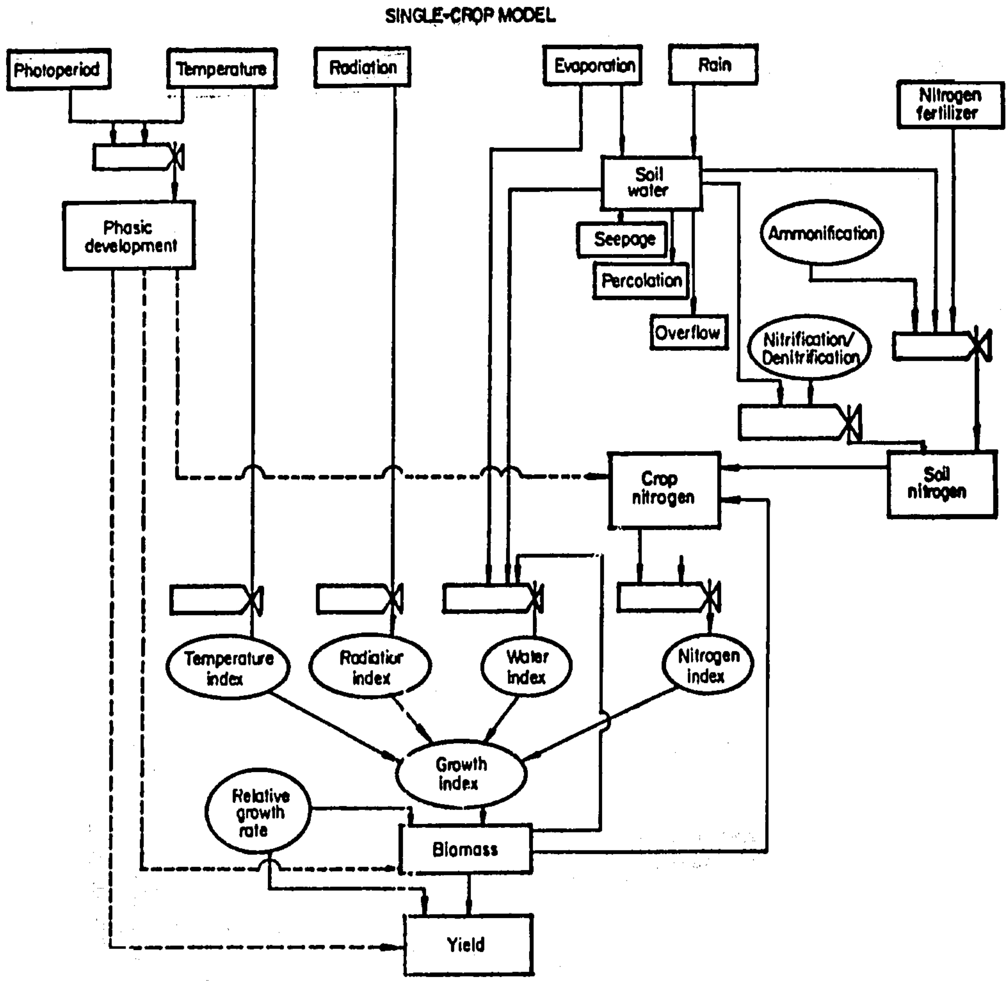
The model reported here shows how important processes leading to crop growth and development can be combined mathematically. A more detailed description is given by Angus (1979). The top line of Figure 1 shows the necessary weather parameters.

Unconstrained growth

In optimal environmental conditions the growth of crop biomass can be described by a sigmoid curve such as that produced with the Gompertz equation (Thornley 1976). This can be expressed as a differential equation:

$$\frac{dW}{dt} = \alpha W e^{-\beta t} \qquad (1)$$

where, W is biomass, t is time, and α and β are constants with α equivalent to the relative growth rate at the beginning of



1. Flow chart of a model for rainfed wetland rice.

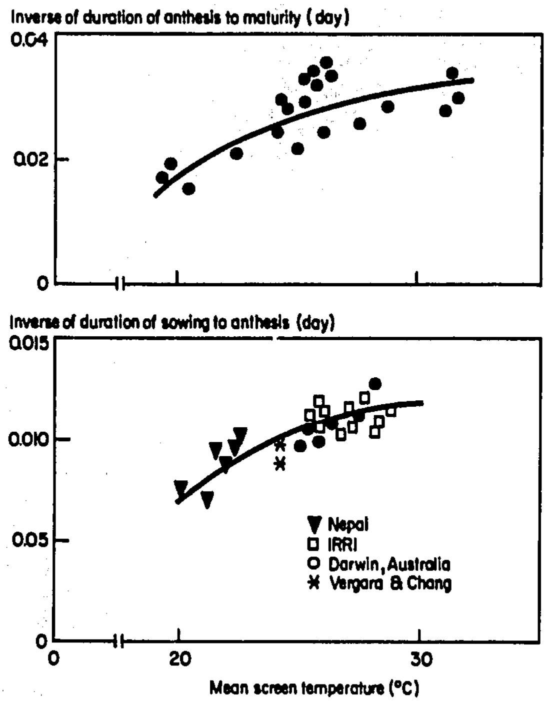
the crop cycle, and β defining the decrease in α with time.

This equation has deficiencies as a crop model. (1) The use of a differential form is unrealistic because weather data are at best available only on a daily basis. A difference equation with a daily time step is proposed. (2) The use of calendar time (t) is also unrealistic; it is well known that crop development rate depends on temperature and photoperiod as well as on time. Some measure of biological time is necessary. (3) The effects of environmental and management constraints that reduce growth to less than optimal levels are necessary.

Phasic development

Temperature and photoperiod affect the duration of rice's life cycle phases. Temperature affects the duration of all phases of all cultivars; photoperiod affects the duration of only the preanthesis phases of some cultivars (Vergara and Chang 1976). The development of the grain-filling phase can show the effect of temperature alone, and IRRI data (1965) have been transformed to show the effects of temperature on development rate, here expressed as $1/D$, where D is the duration of the phase in days (Fig. 2). A nonlinear equation gives a better fit to these data that does a straight line, suggesting that the day-degree or heat unit system (which assumes a linear response to temperature) is inappropriate for rice growing in the humid tropics.

Rice can be classified as a short-day plant because of its photoperiod sen-



2. Rate of phasic development of IR8 rice in relation to temperature for a) the phase from anthesis to maturity, and b) the phase from sowing to anthesis (IRRI 1965; B. S. Vergara, personal communication; Vergara and Chang 1976).

sitivity prior to anthesis. This trait varies widely among cultivars, and many modern varieties show minimal sensitivity. For example, the anthesis date for IR8 was 101 days after sowing in a constant photoperiod of 10 hours, and 109 days in a constant photoperiod of 14 hours (Vergara and Chang 1976). The data shown in Figure 2 (B.S. Vergara, personal communi^ation) suggest that the rate of development prior to anthesis also has a nonlinear response to temperature.

The model of phasic development is used to calculate the accumulated development ($\Sigma 1/D$) completed at any time. When $\Sigma 1/D = 1$, the life cycle is complete. Before maturity, $\Sigma 1/D$ is used as a measure of biological time in the Gompertz growth equation (1), and is used to estimate the anthesis date when biomass allocation to grain growth begins.

Environmental and management constraints

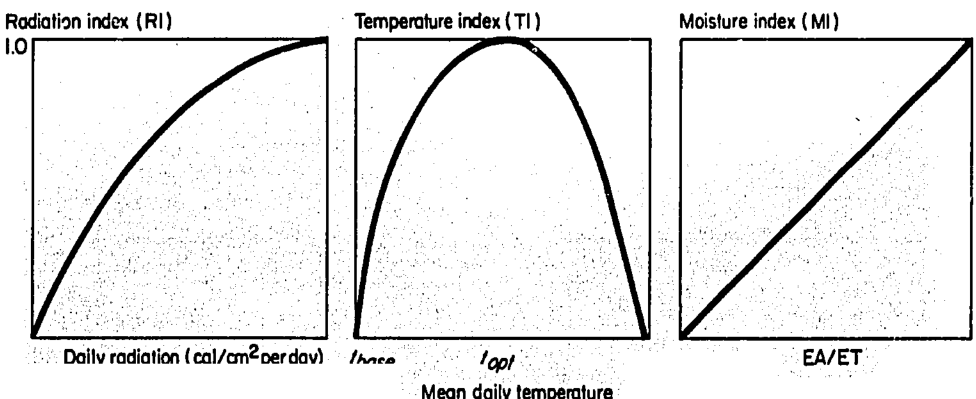
Fitzpatrick and Nix (1970) devised a growth index that has been widely used in relating growth to radiation, temperature, and moisture using a multiplicative equation:

$$GI = RI \times TI \times MI$$

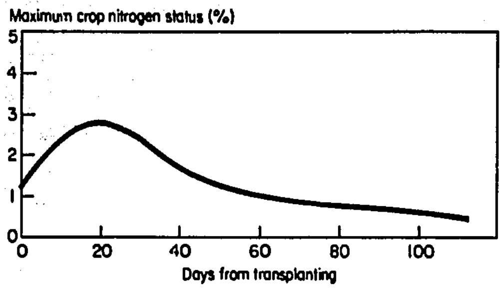
where, *RI* is the radiation index, *TI* is temperature index, and *MI* is the moisture index.

Each of the three environmental indices is scaled between 0 and 1. When each is nonlimiting, *GI* is 1. When one factor is reduced, the *interaction* is simulated by the products. When more than one factor is limiting, the effect on *GI* is dominated by the lowest of the three indices.

The three environmental indices are estimated from relationships that represent the effect of the actual environmental factor on crop performance (Fig. 3). In addition, the effect of crop nitrogen status is introduced into the Growth Index after postulating a maximum crop nitrogen status (MCNS). MCNS can be estimated from analyses of crops grown on



3. Components of the growth index in relation to radiation, tempera^ure, and the ratio of actual to potential evaporation (EA/ET) (Fitzpatrick and Nix 1970).



4. Change in crop nitrogen status in a rice crop with luxury nitrogen supply.

luxury applications of nitrogen fertilizer (Fig. 4). The actual proportion of nitrogen can be computed from cumulative uptake (discussed next) and the computed biomass. The degree of nitrogen stress is then estimated from the ratio of actual nitrogen proportion in the crop tissue to the maximum crop nitrogen status proportion for a given stage of development (d):

$$\left(\frac{\text{crop } N}{W}\right) \times \left(\frac{1}{MCNS_d}\right)$$

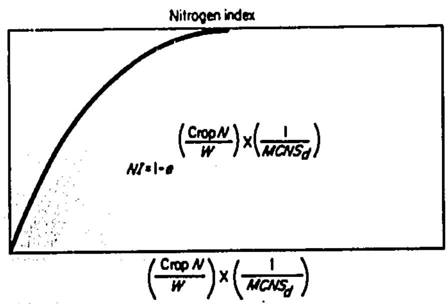
This expression affects crop growth by means of a nitrogen index (NI), which is defined in Figure 5. The growth index is redefined as:

$$GI = RI \times TI \times MI \times NI \qquad (2)$$

Water balance

The water balance of rainfed wetland rice, like that of any other crop species, is affected by rainfall (R) and actual evapotranspiration (EA). But the water balance of a single rice field is a somewhat artificial concept because the lateral flow of water across the landscape is not adequately considered. This topic is covered later.

The water balance of rainfed wetland rice also differs from that of upland crops in that rice is grown on flooded puddled soil whose crumb structure is destroyed, pore space is greatly reduced,



5. Nitrogen index, a proposed component of the growth index, expressed in relation to crop nitrogen status and the maximum crop nitrogen status at a particular growth stage.

bulk density is increased, percolation rate is decreased, and the roots are confined to a shallow layer in which the soil water is generally a single perched water table.

In this version of the model the water balance of a single leveled and bunded field on day i is represented by equation 3:

$$PW_i = PW_{i-1} + R_i - E_{crop_i} - E_{soil_i} - SP_i - OF_i \qquad (3)$$

where, PW_i is perched soil water content in millimeters,
SP_i is seepage and percolation in millimeters/day,
OF_i is overflow from the field in millimeters/day,
E_{crop_i} is transpiration from the crop, and
E_{soil_i} is soil evaporation.

Soil evaporation. Water from the field can be lost to the atmosphere through evaporation from either soil or water, and transpiration from the crop. In the absence of a crop the evaporation rate from a wet soil surface is similar to that from an adjacent evaporation pan, but as the field dries the evaporation rate from bare soil is limited by the rate of water movement to the soil surface. In upland soils the rate of water loss has been described in terms of first and second stage evaporation by Ritchie (1972) who has written a computer program to simulate the process. The program has been modified for use with puddled soil.

Transpiration. Water loss from a crop surface is simulated by a procedure that assumes that when the water supply is adequate, the rate of transpiration can equal pan evaporation, and may even exceed it during the most active growth stage (Tomar and O'Toole 1978). Before reaching a full canopy, the rate of transpiration is related to the degree of canopy cover in upland crops (Ritchie 1972). A similar relationship has been found in wetland rice (F.R. Bolton, personal communication, 1979).

When the soil water supply is inadequate transpiration at both full and incomplete canopy cover is limited. In upland crops, actual transpiration has been related to potential transpiration as a function of soil water content (Denmead and Shaw 1960; Ritchie 1972); in some circumstances, $E_a = E_t$ for soil water values well below field capacity.

Hasegawa et al (1979) show a similar relationship for dryland rice, except that the effect of stress is encountered at higher levels of soil water for rice than for other upland crops. F. R. Bolton's findings for wetland rice also follow the pattern (personal communication, 1979), with the ratio of actual to potential transpiration falling as the soil water content declines. In both dryland and wetland rice, EA/ET falls at levels of soil water close to saturation.

Seepage and percolation. Seepage and percolation are normally discussed and measured together because their action on the *uphill* field is identical. However, their effects on the *downhill* field differ. In considering a landscape model, these processes must be separated. This will be done in a later section but, at this point, we lump them together.

We assume that loss from seepage and percolation is related to the depth of standing water, and the rate of loss is lower when the soil is below saturation (Le Ngoc Sen and Wickham 1977).

Nitrogen in soil and crop

Crops (including rice) can take up nitrogen in both the ammonium and nitrate forms. Both can be supplied from mineralization of organic matter, from fertilizer, and from dinitrogen fixation. The level of NO_3^- and NH_4^+ in the soil will depend on the rates of input and on the rates of loss or transformation by nitrification or denitrification, volatilization, and crop uptake.

Under luxury conditions, the total uptake may be limited by the crop's ability to utilize available nutrients. In farmers' fields, the limiting factor is the supply of soil nitrogen. The simulation model considers both possibilities.

Demand-limited uptake. Nitrogen uptake is limited by demand rather than by supply when the proportion of nitrogen in the total biomass reaches maximum. The maximum depends on development stage (Fig. 4), and is determined by tissue analysis of crops grown under luxury supply. At that level the crop is unable to utilize further soil nitrogen and appears able to exclude nitrogenous compounds from the roots.

When the calendar time scale in Figure 4 is replaced with a development time scale, the experimentally derived values can be used in a simulation model to define the envelope of maximum values of crop nitrogen.

Supply-limited uptake. To simulate the crop's supply of soil nitrogen it is first necessary to simulate the major processes controlling the supply, transformations, and loss of NH_4^+ and NO_3^-. These processes interact to give certain levels of NH_4^+ and NO_3^- on day_i:

$$NH_4 = NH_{4i-1} + \text{Mineralization} - \text{nitrification} - \text{volatilization} - \text{uptake}$$

$$NO_3 = NO_{3i-1} + \text{Nitrification} - \text{denitrification} - \text{leaching} - \text{uptake} \quad (4)$$

1. *Mineralization/ammonification.* Under flooded conditions, the process of mineralization is almost completely the transformation of organic matter into NH_4^+, and is more correctly called ammonification. Ammonification occurs rapidly after initial flooding; later the rate declines. The process can be described with an exponential equation.

The effect of soil water content on ammonification rate in puddled soils has not been closely studied, but we assume that the rate is zero in sufficiently dry soil. Between this point and full saturation, the rate is positively related to soil water content.

Because ammonification is temperature dependent (Ponnamperuma 1972), the time scale is changed from calendar time to *day-degrees.*

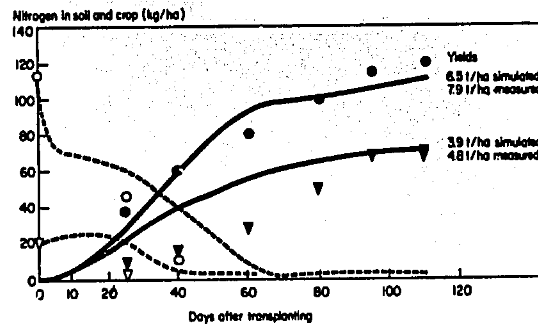
2. *Nitrification.* Under flooded conditions ammonium is the stable form of soil nitrogen; when the soil dries, it is converted to nitrate by aerobic bacteria. In dry soil, this process can be described by a half-life equation.

3. *Denitrification.* In flooded soil, nitrate is reduced to nitrogen-containing gases, which are lost to the soil system. Denitrification is simulated in the model as a half-life reaction analogous to that of nitrification.

The data of Patrick and Wyatt (1964) suggest that denitrification can be simulated as a half-life reaction; however, the effect of water content on the process has not been shown quantitatively. The simulation of both nitrification and denitrification is not based on well-established relationships. Data on which to formulate a more precise relationship are needed.

Partitioning of assimilates for grain growth. Yield is formed mostly from growth after anthesis, but some contribution to yield may arise from reserves which were accumulated before anthesis. Storage reserves may be particularly important when yield is reduced by a stress (Yoshida 1972). In studies of the physiology of grain yield formation, the contribution of reserves to grain growth is commonly expressed as a proportion of final yield. This *ex post* concept is inappropriate for predictive simulation. A more appropriate measure is the proportion of anthesis biomass that is diverted to the grain.

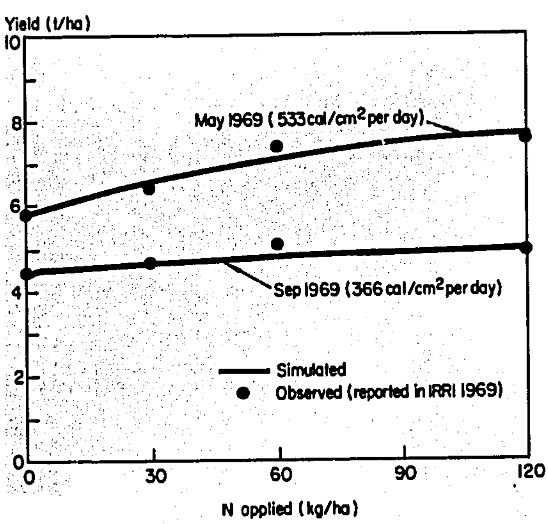
The model assumes that daily grain growth consists of all the current growth plus a proportion of the anthesis biomass which depends on stress (a stress index *SI* is proposed in which $SI = 1 - GI$), with a defined small proportion (5-10%) translocated with no stress, and a larger proportion translocated when stress is greater. The rate at which pre-anthesis reserves are translocated to the grain depends on the rate of phasic development during grain-filling.



7. Comparison of simulated and measured nitrogen balance for irrigated IR26 growing in the 1974 dry season at IRRI. Open symbols refer to soil ammonium; closed symbols refer to crop nitrogen. Circles refer to a fertilized treatment (116 kg N/ha), and triangles refer to a zero fertilizer treatment.

MODEL TESTS

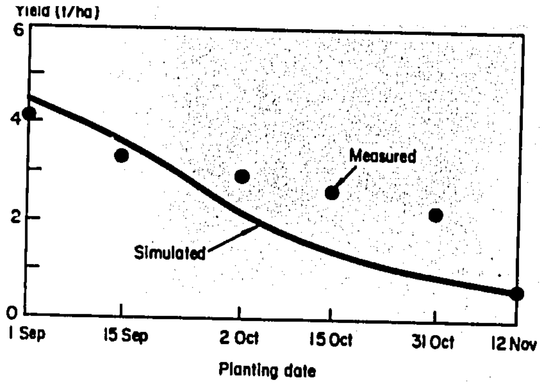
Comparisons of observation and simulation determine the usefulness of simulation as a tool. The interaction between radiatio and nitrogen supply was investigated by simulating a nitrogen experiment with irrigated IR20 at IRRI in the 1969 dry and wet season (IRRI 1969). The constants of the Gompertz equation were adjusted to give a maximum biomass of about 17 t and the maximum amount of soil nitrogen which could be mineralized in the life of a crop. All other constants were obtained from the literature or from discussions with colleagues. The resulting simulation gave surprisingly good agreement with the data (Fig. 6). The result suggests that the model can qualitatively describe the interaction between radiation and nitrogen supply.



6. Comparison of simulated and observed yield of IR20 rice grown under irrigated conditions at Los Baños, Philippines. Data from IRRI Annual Report 1969.

Closer examination of the nitrogen dynamics for fully irrigated crops was made possible by comparing simulated results with the observations of Shiga and Ventura (1976) (Fig. 7). The simulated yields were somewhat lower than those observed perhaps because of varietal effects and the fact that no changes in systems parameters related to yield potential were made. More importantly the soil nitrogen was consistently overestimated. The initial crop nitrogen uptake with zero fertilizer input was also overestimated; however, the final estimated nitrogen uptake was accurate. This result suggests that the previous accurate simulation of the radiation x fertilizer interaction was due to counterbalancing errors, the major one involving soil nitrogen losses after transplanting.

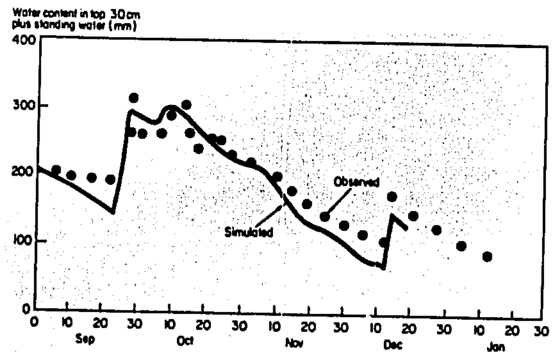
Data for the simulation for rainfed rice came from a time-of-planting experiment conducted by F.R. Bolton in Iloilo, Philippines. IR36 had been transplanted on a sideslope landscape position at 2 weeks intervals beginning in September 1975. Simulation and observation (Fig. 8) showed good agreement at the beginning and end of the experimental period, but simulation seriously underestimated yield in the middle of the period, per-



8. Comparison of simulated and measured yields of IR36 for 6 successive plantings in 1978 at Cordoba Sur, Tigbauan, Iloilo. Measured data are from the experiments of F. R. Bolton.

haps because the model underestimated soil water and overlooked lateral flow. A comparison of simulated and observed soil water is shown in Figure 9.

Bolton's experiment included treatments with varying rates of nitrogen fertilizer and different planting dates. The data in Figure 8 refer only to the treatments receiving maximum fertilizer (120 kg/ha N). By re-running the simulations with different levels of applied nitrogen for each planting date, the model's sensitivity to the important interaction between drought and nitrogen supply was tested.



9. Simulated and observed estimates of water content in the top 30 cm of soil plus standing water of a sideslope puddled field in Cordoba Norte, Tigbauan, Iloilo. Observed data from experiments of F. R. Bolton.

As in the water-balance test shown in Figure 8, the yields of the third, fourth, and fifth plantings were underestimated. The simulated nitrogen responses of the various plantings were more satisfactory: for example, the simulated yield response to nitrogen application was 1.5 t/ha in the first planting and a negative 0.1 t/ha in the sixth. Both simulations were within the range of observed responses and were judged to be qualitatively reasonable.

Results of water balance tests suggest that neglect of lateral flow in the model leads to consistent errors.

TOPOSEQUENCE WATER BALANCE

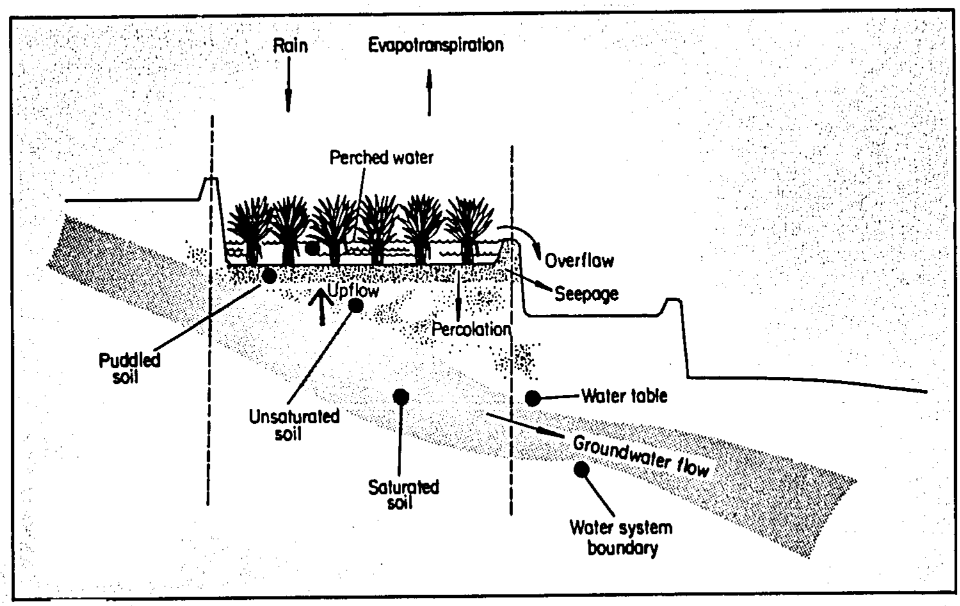
The effect of landscape position on the yield of rainfed rice growing on a toposequence is well known (Moormann et al 1977), and crops in low landscape positions commonly outyield high-landscape crops, particularly if planted late in the rainy season. We made a preliminary attempt to account for the lateral flows of water between fields in an undulating landscape. The flows considered are shown by arrows in Figure 10, and described in more detail by Angus (1979).

Data for testing the model came from experiments by H.G. Zandstra and A.N. Villegas (personal communication) who made weekly measurements of soil water content plus the free water level of three adjacent puddled, rainfed fields at IRRI during 1978. The fields were each about 20 m wide and 30 cm apart. The measurements are shown as smoothed solid lines (Fig. 11) representing the water available to rice (volumetric water content of the top 30 cm of soil plus standing water) for the top, middle, and low fields of the toposequence.

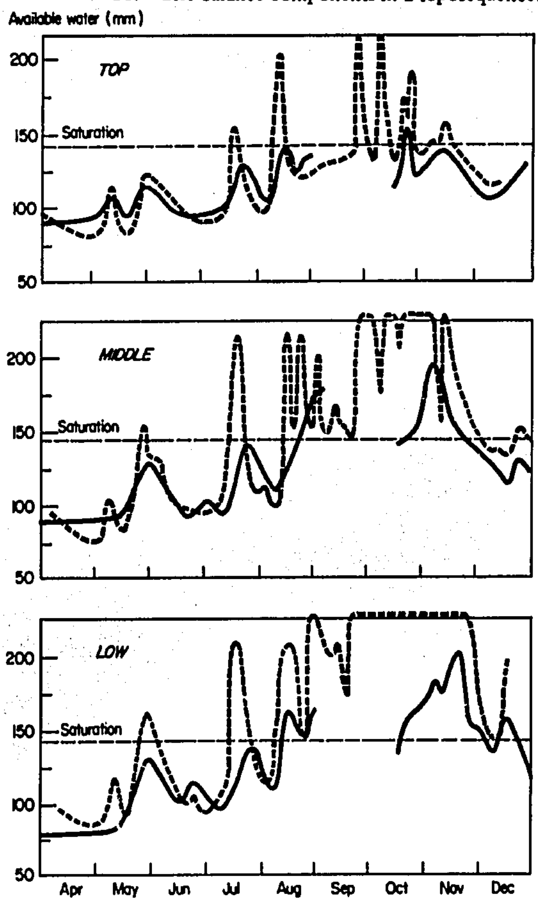
The model calculations (Fig. 11) generally agree with observations of the relative wetness of the three fields -- the water content of each was simulated with reasonable accuracy during periods when the landscape was unsaturated. But the model was poor in duplicating the observed variations in free water levels. This may have been due as much to water lost into drains and difficulties in maintaining tight bunds as to any deficiency in the model.

DISCUSSION

The simple model presented here is directed towards some major environmental and agronomic constraints on wetland rainfed



10. Water balance components in a toposequence.



11. Water balance of three adjacent rainfed rice fields in a toposequence at IRRI during 1978. Water content in each field is water in the top 30 cm plus free water. No measurements were taken in September or the first half of October. Simulated values are shown as dotted lines.

rice -- radiation, temperature, water stress, and nitrogen supply. Tests showed that despite the model's simplicity, its calculations were qualitatively reasonable and, in some cases, quantitatively accurate.

The problems with the simple water balance when applied to a terraced field, and the measure of success when the toposequence water balance was used suggest that the effects of landscape need further consideration. The inaccuracies in the nitrogen budget, and the difficulties in obtaining basic information on the nitrogen balance of rainfed fields suggest that *the nitrogen aspect* also needs more attention.

Crop simulation models in use are continously being refined. Rather than elaborate on or defend particular algorithms that may later be improved upon, we would emphasize the advantages of simplicity in a model and the need to account for the factors responsible for most of the yield variation. A simple model can easily be programed in a computer, and the program can be readily used and modified by colleagues with computing facilities. It is also valuable in teaching undergraduate and graduate students.

This simple model can be used for the formal optimization of parameters.

Recent developments in the methodology of crop growth simulation (Sands et al 1979) have shown that parameters can be optimized by including a model as part of an optimization program in which each iteration of the main program involves a complete run of the crop model. Calculated crop production is compared with measured production after each iteration. Such a process requires many iterations, and computing costs become prohibitive if a complex model or one with a short time-step is used.

Another advantage of simplicity is that the model can be used as a *workbench* on which other components can be tested or refined. It is available in BASIC language for use on a minicomputer by researchers who wish to test or refine the existing model or who wish to add new components.

Probably the greatest deficiency of this model in representing a real rice crop is that it does not take biotic factors into account. A formidable array of pests attacks rice and each pest interacts in distinctive ways with the environment and state of the crop. Unfortunately the basic environmental biology of most pests is not known well enough to provide an accurate simulation of pest damage. An attempt has been made to simulate damage by the brown planthopper, a pest which has been studied extensively, by accounting for the insect's feeding behavior (Kenmore and Angus 1979). The results are encouraging, but much work remains if simulation models of environment, crop, and pests are to be useful for rice research.

Incorporating a model into a regional research framework

Once a model has been developed to the stage where it accounts for the major yield factors in a region, the model can be made part of the whole system of regional agricultural research by adopting a systems framework for the crop and agrometeorology data-collecting (Angus et al 1974). To apply a model this way, there is need for a regional experimental program to collect balanced set of crop and environmental data (Angus 1980), and a bank of regional weather data with which the model can be used.

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A conceptual agromet rice yield model

J. W. Stansel and R. E. Fries

A data base driven agromet model for predicting rice yields is discussed. The yield predictions are based on a convergence of evidence from two models, a yield reduction model that interprets current meteorological data, and a yield variances model that interprets the variance between current meteorological data and their historic means. A phenology model provides a sensitivity analysis of meteorological factors as they influence rice yield at each stage of plant development. The models identify stress parameters so precise yield evaluations can be made, and provide a confidence level in the estimates and a means to troubleshoot for increased precision.

Crop yield models are simplified representations of the complex relationships between variables that comprise crop environment and crop performance using established mathematical or statistical techniques or both (Baier 1977). These models can be relatively simple, such as the *stress degree day* model (Idso et al 1977) in which temperature and moisture levels are related directly to final yield. The models can also be complicated, such as some of the Large Area Crop Inventory Experiment (LACIE) models which use remote sensing (radiance), statistical, and agrometeorological data in combination to monitor and forecast wheat yields (MacDonald and Hall 1977).

Rice, adapted to a greater range of climatic and cultural conditions than any other single cereal, is grown over a wide range of latitude, climate, soil, and water conditions. This paper will examine the influence of agrometeorological variables on the specific development stages of rice as the basis for developing a universal rice yield prediction model.

AGROMETEOROLOGICAL VARIABLES IN RICE PHYSIOLOGY RELATIONSHIPS

Moisture

Water is the main determinant of rice cropping and yield. Moisture amounts and distribution are especially important during the reproductive stage and during the first 15 to 20 days of the grain filling and maturation stages.

The moisture requirements of the rice plant are normally expressed as a function of evapotranspiration (ET). The ET requirement in a field environment is about 4.0 mm/day during the vegetative stage and during the medium dough to hard dough stages of maturation. During the reproductive stage and up to the medium dough stage (about 15 days after heading), the ET requirement is about 6.0 mm/day (Robertson 1975, Yoshida 1977). Precipitation must meet ET requirements plus losses due to infiltration and percolation. Because the infiltration rate may limit the amount of moisture absorbed by the soil, precipitation at rates above infiltration becomes ineffective if not contained. The percolation rate largely determines the moisture-storing capacity of a soil. The higher the percolation rate, the higher the precipitation amounts and frequency needed to produce a crop. The amounts of rainfall needed are about 200 mm/month during the vegetative stage and from the medium to hard dough stages, and about 300 mm/month during reproduction up to the hard dough stage (Yoshida 1977). These monthly effective moisture levels do not include losses from runoff or percolation. In areas without irrigation or sufficient water catchment, the termination of the rainy season

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relative to the heading stage would have a major effect on yield if the ET needs of the plant are not met.

Temperature

Subspecies characteristics. Minimum daily temperatures determine the effective growing season for rice. When daily temperatures fall below 10°C for 3 or more consecutive days during grain filling and maturation, effective yield is stopped in indica cultivars. Japonica cultivars, however, can generally develop at temperatures 2-3°C lower. The survival and growth temperature ranges of japonica x indica crosses do not encompass the total combined range of both subspecies.

Designating rice cultivars as japonica or indica is an inaccurate way of differentiating temperature reponse capabilities because many varieties are crosses of both. Therefore, we will use the terms *warm temperature* (WT), *intermediate temperature* (IT), and *cool temperature* (CT) cultivars.

Phenology relationships. The influence of temperature on rice grain yield varies with development stage. At one stage, temperature may be positively correlated with grain yield while at another the correlation may be negative. Within the ranges of 18°-35°C for WT cultivars and 15°-33°C for CT cultivars, temperature correlates positively with plant growth during the vegetative stage. However, correlations are generally negative and of a higher magnitude at later stages. During the reproductive stage temperature has both catastrophic (zero yield) and significant quantitative (high % yield reduction) yield impact potential.

The time required for the plant to develop from establishment to the reproductive stage is largely a function of cultivar. Cultivars can be split into three broad maturity groups. Group one encompasses varieties (most indica cultivars) that are sensitive to photoperiod and thus require a critical length of day to trigger panicle development. Generally, these varieties have long season maturity when grown in their adapted environment. The japonica cultivars are generally insensitive or only weakly sensitive to day length. These photoperiod-insensitive cultivars are usually early or very early maturing types. The number of days from plant establishment to the reproductive stage becomes a function of accumulative temperatures units. Accumulative temperatures units are defined as mean daily temperatures above 10°C but do not exceed 15 units for any single day. This is called the *Degree Day 10* concept (DD10°C/15). In some cultivars temperature and day length interact. This third group requires a base accumulation of temperature units and a required day length to trigger panicle development. These are intermediate season maturing cultivars.

Determining the beginning of the reproductive stage from the time of plant establishment can be very difficult. However, the period from the beginning of the reproductive stage to first heading is relatively constant. Since heading is easy to recognize, it becomes a useful tool for determining the beginning of the reproductive stage for modeling purposes. About 500 DD10°C/15 units (approximately 20 days) are required from panicle bud initiation to heading. This becomes 500 to 600 DD10°C/15 units under high and uniform plant populations and 500 to 700 DD10°C/15 units with transplanting.

There are three development phases during the reproductive stage when low temperatures can have catastrophic effects on yield. The first phase occurs when temperatures fall below 15°C during panicle initiation and the number of florets per panicle is greatly reduced.

The second phase occurs during meiosis (Satake 1976), about 10-12 days before first heading (about 250 DD10°C/15 units before heading), when the leaf collar of the flag leaf and the most recently developed leaf pass each other as the flag leaf is extending. Injury at this time is a function of low temperature, temperature duration, diurnal temperature fluctuations, and varietal differences (Yoshida 1977). The amount of sterility can be crudely defined by the equation:

$$(\text{\% sterility at meiosis})^{*} = \frac{(\bar{x}\text{ daily temp} - 20^\circ\text{C})(\text{no. days temp is below } 20^\circ\text{C})}{(\text{diurnal temp range} + 1)(-10)} \times 100$$

*negative values = 0, maximum < 100%. Use 20°C in formula for WT cultivars and 17°C for CT cultivars.

The third (and most important) phase,

anthesis, normally occurs 1 to 3 days after a floret has emerged from the flag leaf sheath and continues for about 14 days. Temperatures below 22°C for WT cultivars reduce pollen maturity and therefore influence floret sterility. The sterility becomes a function of the percentage of florets at the anthesis stage x the number of days temperatures are below 22°C. Assuming anthesis occurs for a full 17-day period, the percentage distribution of florets should follow a normal distribution curve starting at the time of first head. The curve should peak at 8-9 days when about 25% of the florets have undergone anthesis.

Pollination normally occurs during the period from 3 to 8 hours after sunrise. Under high sunlight, anthesis occurs earlier in the range. Overcast skies delay anthesis. However, high temperatures or high winds or both during anthesis can cause pollen desiccation. Therefore, the combination of when anthesis occurs in relation to when temperatures above 35°C occur for WT cultivars determines the degree of pollen sterility. Critical temperature values for CT cultivars at all stages are 2-3°C lower than for WT cultivars.

The relationship between temperature and yield during rice's reproductive stage is similar to that found in other Gramineae grain crops, assuming no overriding (catastrophic) temperature effects occur. Within specified temperature ranges for a given cultivar, temperature during the reproductive stage is generally negatively correlated with grain yield (Munakata 1976). The ideal climate for yield during the reproductive stage would be a diurnal temperature range of 31°-22°C under high levels of sunshine. With adequate sunlight, both photosynthesis and respiration increase as temperature increases to 31°C. However, since respiration is a 24-hour photosynthate breakdown phenomenon and photosynthesis only occurs in the presence of sunlight, the net balance in photosynthates available for panicle floret production decreases as night temperatures increase from 22°C. When day temperatures fall below 22°C, photosynthesis is reduced more than is compensated for by the reduced respiration. Under low sunlight, low temperatures reduce the rate of photosynthesis and thus limit the amount of photosynthates produced and available for floret production and differentiation. Above 31°C, photosynthesis is reduced while respiration continues to increase for several more degrees before starting to decrease also. High respiration rates also tend to produce excessive vegetative growth, which can reduce yield by causing shading, lodging, and increased incidence of diseases and insects (Nishiyama 1976). Because long-season cultivars are in the vegetative stage longer, more carbohydrate is stored in the leaves and culms for floret development and grain filling than in early-maturing cultivars. Consequently, short-run weather variations do not have as direct an effect on the yield of long season cultivars, and they do not require management inputs as extensive as those for the early-season cultivars. The early-season cultivars have higher yield potential but greater yield variation.

Grain filling and maturation begin after the ovary has been fertilized. Normally about 15% of the florets will not be fertilized (Chang and Oka 1976). Floret size is essentially a cultivar characteristic and therefore places an upper physical limit on grain size and shape. Weather conditions influence yield at this stage by determining the extent to which each floret will fill. The temperature maturity group relationship with photosynthesis in the reproductive stage carries over to the medium-dough stage of maturation.

High temperatures during the ripening stage can accelerate maturation by reducing grain moisture content too rapidly and cutting off the carbohydrate supply prematurely. The result is smaller grain of low quality. A negative correlation exists between grain yield and temperature during this period. Low nighttime temperatures favor ripening, perhaps by reducing the rate of respiration. As the grain develops, the influence of photosynthesis on grain filling begins to diminish. The combination of lower respiration and reduced grain moisture loss with progressively lower temperatures increases yield. As the grain develops, the mean optimum air temperature decreases progressively from 21° to 14°C. Levels of sunlight interact with temperatures during the grain filling and maturation stages (Stansel 1975). The high temperatures accelerate ripening while the low light conditions limit carbohydrate production and reduce grain yield (Stansel and Huke 1975).

Solar radiation

Analysis of the relative importance of solar radiation on grain yield shows that the reproductive stage is influenced most, and the ripening stage next. The overall effect of solar radiation during the vegetative stage on grain yield is extremely small. A yield of 4 t/ha can be obtained with 200 cal/cm^2 per day during the reproductive stage. The same yield can be attained with less solar radiation during the ripening stage. Thus, it is unlikely that incident radiation limits rice yield in most countries where the national average is below 4 t/ha (Yoshida 1977).

When cloudy weather during ripening restricts photosynthesis, stored carbohydrates support rice growth despite weather fluctuations. Experiments indicate that stored carbohydrates can account for yields of about 2 t/ha in long-season cultivars. Therefore, solar radiation does not normally limit yields until limiting factors such as soil moisture, temperature, diseases, and insects are removed. As yields become greater than 4 t/ha, factors such as the leaf area index, leaf angle, peak radiation, and day length become important in determining how effectively solar radiation determines yield (Yoshida 1977).

Catastrophic events

Temperature. In addition to the low temperatures inducing catastrophic impact on yield, high temperatures (35°C or greater for WT cultivars, 33°C or greater for CT cultivars) can also drastically reduce yields at heading (pollination).

Wind. High winds in the forms of typhoons or hurricanes and accompanied by flooding can cause sterility during anthesis. Lodging induced yield losses result from reduced photosynthate movement because of damaged plant structures, reduced grain filling, or losses due to grain spoilage.

Floods. Floods early in the growing season can require replanting. This may not be critical in tropical areas because growing seasons are long enough to provide flexibility in planting dates. There is some evidence that by delaying the planting time of photoperiod-sensitive cultivars, yields can be increased (Yoshida 1977).

Flooding at anthesis can severely reduce yields. Flooding during grain ripening can lead to harvest losses, sprouting of grain, and general deterioration.

Floating rices are grown along many of the floodplains of major rivers. These cultivars can elongate up to 30 cm/day and attain heights of 7 m. Yields are generally low and dependent on such factors as plant age when flooded, rate of increase and final flood level, flood duration, water turbidity, and water temperature.

Pests. Pests include weeds, diseases, and insects. Weather plays a role in determining insect and disease infestations. These weather influences are generally very complex and frequently difficult to model accurately.

Crop-environment interactions

Figure 1 summarizes the preceding discussion and serves as the major basis for the rice model. During the reproductive stage, the crop requirement is highest and an environmental parameter has the most significant impact on yield. Floods are an exception to this rule.

RICE YIELD MODEL CONCEPTUALIZATION

Guidelines

The rice yield model will be oriented to crop physiology and the assessment of the impact of environmental parameters. The model is constructed so that the following guidelines apply:

1. It should produce periodic yield estimates using only meteorological data.

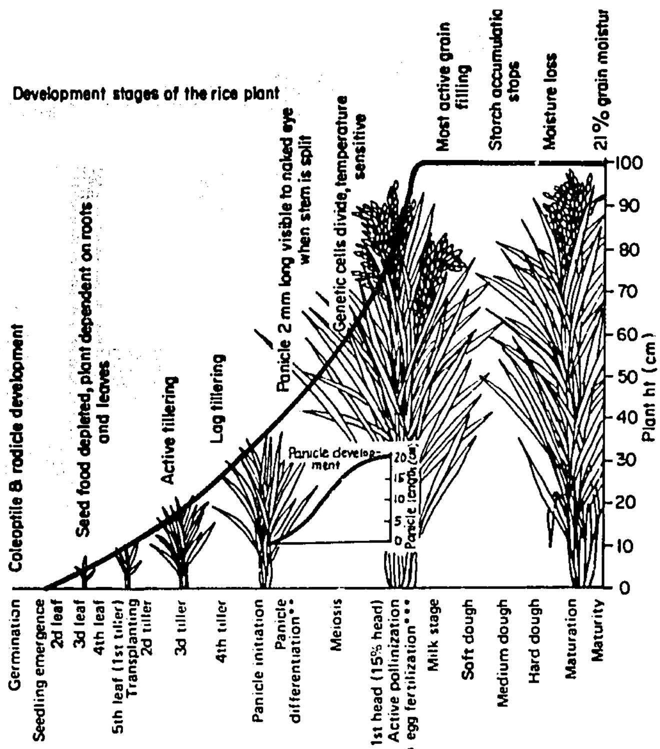
2. It should employ a "convergence of evidence" approach; that is, yield is predicted via more than one calculation mechanism. Similar results increase confidence; different results establish the need for further analysis.

3. It should incorporate a "most limiting factor" concept into the model logic; that is, factors are examined in the order of those having most to least impact on final rice yield.

The model is not static. It changes and becomes ever more precise as new information is gathered. It is not area or site specific, but applies anywhere in the world for any rice culture.

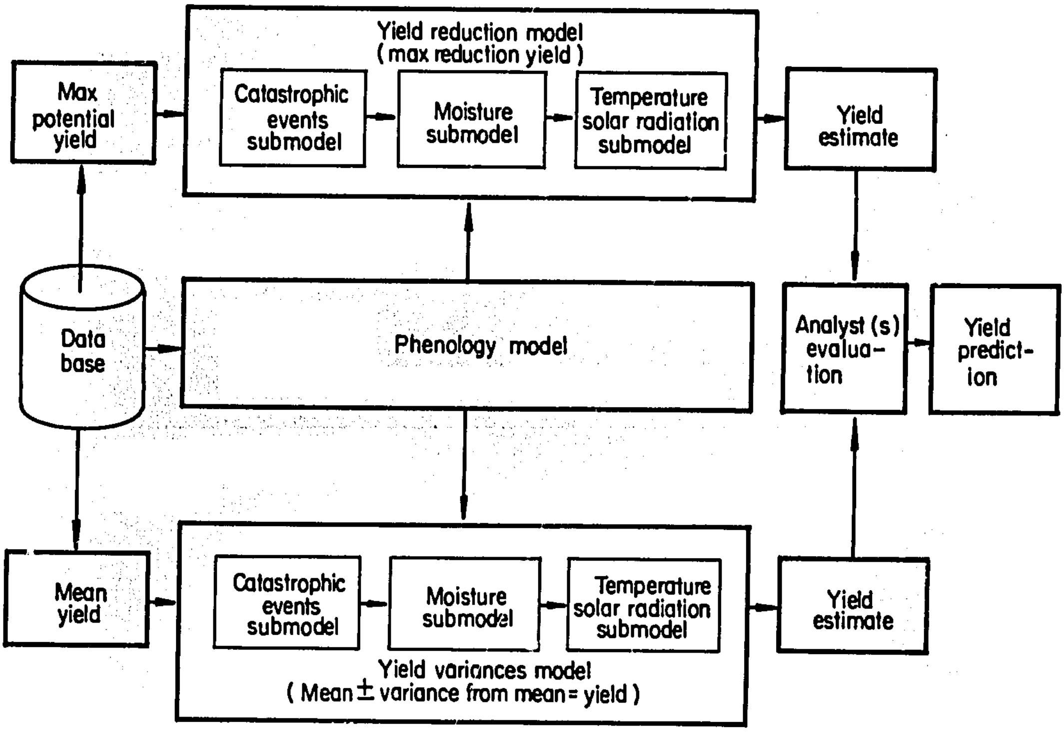
Functional flow overview

The overall yield model has four major components: a data base, a yield reduction model, a phenology model, and a yield variances model (Fig. 2). The data base is the input source to all three models. The phenology model interfaces with the yield reduction and yield variances models, and these in turn provide independent yield estimates. The



	Stage I Vegetative	Stage II Reproductive	Stage III Grain filling & maturation
100°C units	650°C units — Variable day length	300°C units	500°C units
I. Soil moisture	⊢ET 4.0 mm/day⊣ ⊢EM 200 mm/mo⊣	⊢ET 6.0 mm/day⊣ ⊢EM 300 mm/mo⊣	⊢ET 4.0 mm/day⊣ ⊢EM 200 mm/mo⊣
II. Temperature	⊢15°C–35°C⊣ +r (low significance)	⊢22°C–31°C⊣ +r (high signif.)	⊢14°C–25°C⊣ +r (medium significance)
III. Solar radiation	⊢100-300 cal/cm² per day⊣ +r (low significance)	⊢200-500 cal/cm² per day⊣ +r (high signif.)	⊢150-400 cal/cm² per day⊣ +r (medium significance)
IV. Catastrophe			
A. Temp	⊢14°C⊣ ⊢15°C⊣	⊢20°C⊣ ⊢22°C⊣ ⊢35°C⊣	⊢22°C⊣ ⊢35°C⊣
B. Flood	⊢Moderate damage⊣	⊢Moderate dam.⊣	⊢High damage⊣
C. Wind	⊢Low damage	⊣ High damage	⊢Moderate damage⊣
D. Diseases & insects	⊢Moderate damage⊣	⊢High damage⊣	⊢Moderate damage⊣

1. Meteorological effects at stages of rice development for warm-temperature cultivars.



2. Function flow overview of conceptual rice yield model.

final yield prediction value is derived from these yield estimates.

Data base

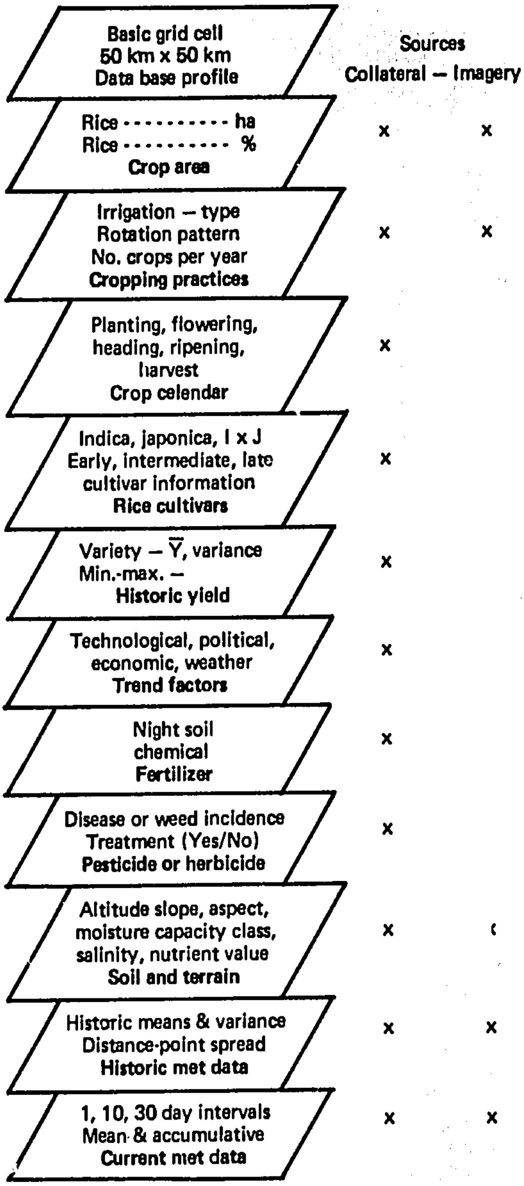
Geographic unit cell size. The decision as to what cell size to use for our model should only be made following analysis of a mosaic of the total area of interest. After delineating agriculture vs nonagriculture at some reasonably small scale, a more detailed study of the agricultural area should provide the principal guidance on cell size. If only national statistics are required, the data cells can be fairly large. Conversely, if the statistics must have high precision at a lower political level, each cell must be smaller. This presumption accounts for the population size contribution to error and recognizes that averaging of heterogeneous surface features (crops, soils, etc.) occurs in larger cells. Generally, a 50 km x 50 km cell is adequate for generating country level yield estimates; a 25 km x 25 km cell may be required for suitable precision at lower political levels.

Contents and design. Data that will be needed for optimum model operation should be gathered, interpreted, coded, formatted, and entered into the data base for retrieval during model execution (Fig. 3). Occasionally, not all these data will be available for each cell. In such cases, judgment will provide critical model driving data (e.g. yield data and crop calendar data), and cell entry locations for noncritical data will be left empty.

Yield reduction model

The yield reduction model assesses the impact of various environmental parameters on yield via catastrophic events, moisture, and temperature and solar radiation submodels. The submodels are operated such that environmental occurrences with the most significant impacts on yield are examined first, followed by those which affect yield to a lesser degree.

Maximum potential yield. A maximum potential yield (MPY) is the starting point for the yield reduction model. MPY becomes a measure of background factors that influence yield in a cell but for which data are not available or are not accounted for in the model. These background factors can be normal pest pressures; soil conditions such as inherent fertility, salinity,



3. Data base design and input data sources.

nutrient balance, texture; or generalized climatic patterns.

MPY is developed from the mean yield of the cell plus three standard deviations above that mean. The value is then adjusted by a trend term which incorporates the influence of variables such as climate, politics, economics, and technology. This trend term generally is not a smooth line from year to year, so a simple regression analysis is not valid.

The MPY can be calculated for any year, but if a historic yield ever exceeds it, then the trend term must be reanalyzed. If after reevaluation a historic yield is still larger than the recalculated MPY, then the highest historic yield plus a trend term is used as the MPY.

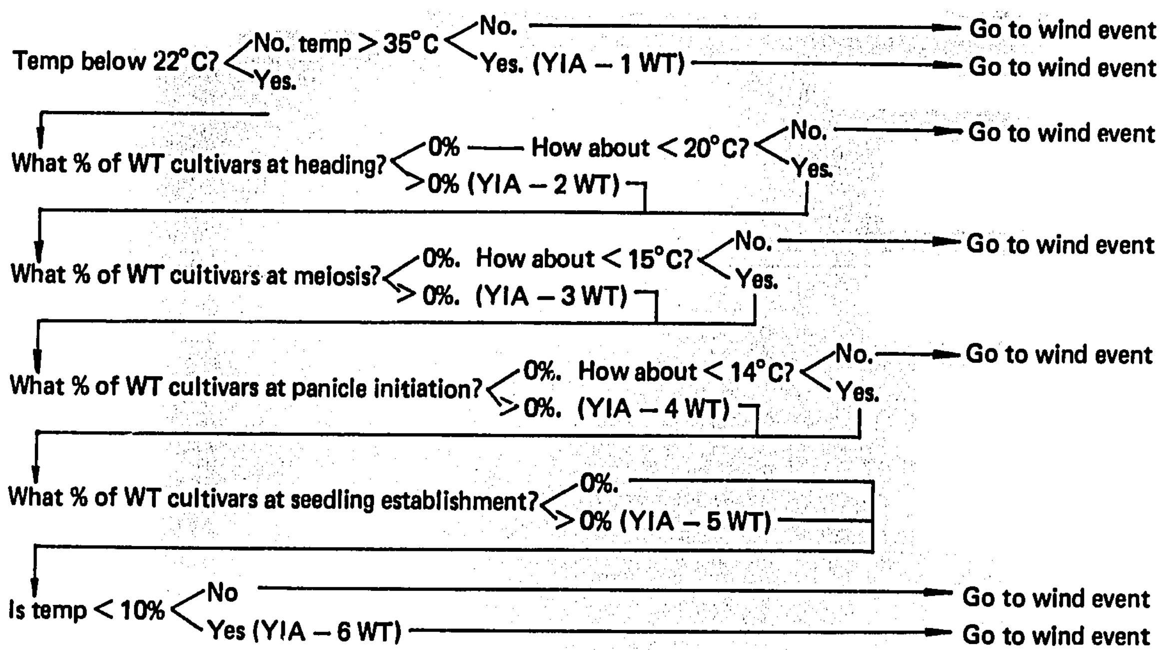
Catastrophic events submodel. The catastrophic events submodel evaluates in the following order: temperature extremes, high winds, flooding, and insects and diseases. The overall internal submodel is governed by a "yes" or "no" logic flow regarding the occurrence of a particular event. When a "yes" is encountered, the impact of that event on yield is assessed; a "no" directs the model to the next event and eventually to the moisture submodel (Fig. 4). Note that Figure 4 is specifically for the WT cultivars. Similar flows would exist for CT and IT cultivars temperature but would have different temperature regimes.

Secondly, note that temperature sensitivity (at the catastrophic level) is dependent on the growth stage -- the sensitive times being headin meiosis, panicle initiation and seedl g establishment. Only at very extr e temperatures -- >35°C and <10°C - will WT cultivars be catastrophicall damaged regardless of growth stage. he 18 yield impact assessment (YIA, points are treated separately because the specific equations used to derive the values (% reduction) are different in each case.

Moisture submodel. Figure 5 represents several moisture-rice relationships. Daily water demand and the sensitivity to moisture stress vary with plant development. Stress is also an intensity and duration phenomenon.

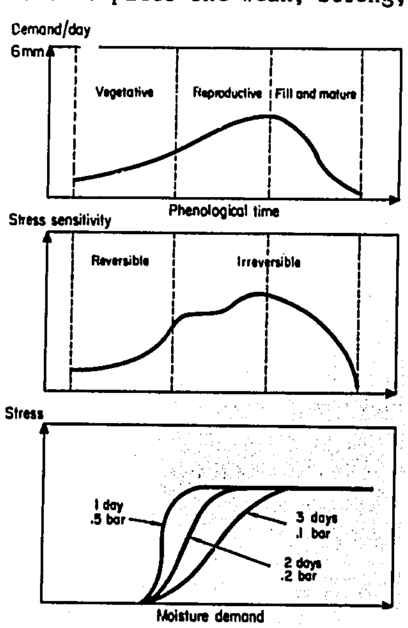
Transplanted rice has a significant advantage over other crops in determining soil moisture budgets because transplanting will take place under saturated soil conditions. The data base will supply the inputs needed for water budget calculations. For rainfed rice cultures, these calculations will use ET, soil percolation, effective precipitation, and a correction factor for the amount of reserve water in the field at transplanting. For irrigated rice, the factors for distribution systems, reserve water supplies, and irrigation well pumping capabilities must be entered into the budget determinations.

Temperature and solar radiation submodel. Figure 6 presents the physiological response of rice to temperature. The optimum growth line plotted indicates a



4. Logic flow for catastrophic events submodel: temperature events. Warm-temperature (WT) series. YIA = yield impact assessment.

change from a positive correlation with temperature during the vegetative stage to a negative correlation during grain filling and maturation. The sensitivity curve depicts the weak, strong, and

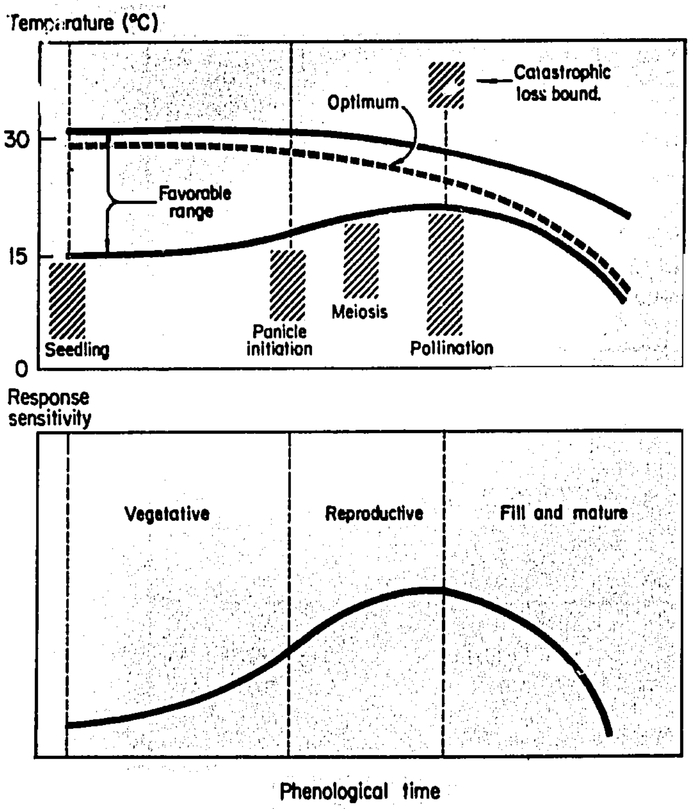


5. Diagrammatic representation of the expression of moisture stress by rice.

moderate relationships between temperature and yield for the respective stages of plant development. The impacts of exceeding critical temperatures at seedling establishment, panicle initiation, meiosis, and pollination will be evaluated by the catastrophic events submodel.

Figure 7 presents the response of rice to solar radiation. The sensitivity response over the course of the growing season is similar to that for temperature, being highest during the reproductive and early maturation phases. The correlation between solar radiation and yield is positive throughout the growing season.

In addition to expressing a development related sensitivity, rice exhibits a significant cultivar and maturity group related sensitivity. The yield of early-maturing cultivars is affected more by temperature and solar radiation variation than is the yield of late maturing cultivars. The temperature and solar radiation interaction mechanism for rice makes it difficult to treat these two parameters separately. Consequently, the two have been combined into a single submodel. During submodel operation, a percent yield reduction will



6. Diagrammatic representation of the physiological response of rice to temperature.

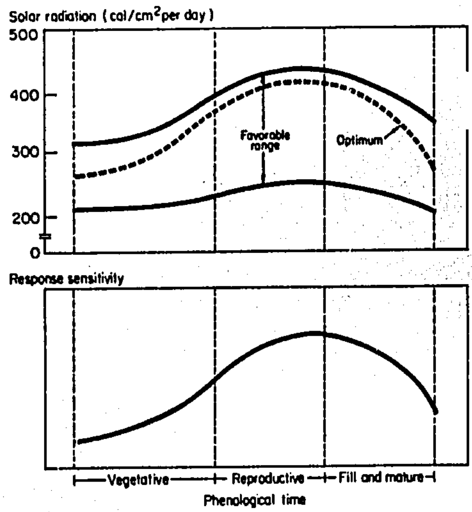
be calculated for a grid cell's particular cultivar or maturity group and then subtracted from the MPY (as modified by any catastrophic event and moisture reductions) to obtain the estimated yield.

Phenology model

The phenology model, the second model operating as part of the rice yield model, supports the yield impact assessments made by the catastrophic events, moisture, and temperature and solar radiation submodels. However, its biological clock outputs are also useful for applications such as interpreting observable and digital image processing results.

The phenology model includes phenology drivers, stress impact, and population variance.

Three general groups of rice cultivars are defined by their relative duration from seeding to maturity (Fig. 8). The length of the vegetative phase determines a cultivar's maturity classification. Once panicle initiation has occurred, all three maturity groups are thermal unit dependent for the remainder of the growing season. The duration of the reproductive and maturation phases varies to some extent among cultivars.



7. Diagrammatic representation of the physiological response of rice to solar radiation.

Stages of development

Maturity group	Vegetative phase		Reproductive phase		Maturation phase
Early	Thermal sensitive 40–50 days (600°C–750°C units)	Panicle initiation	Thermal sensitive 21 days (300°C units)	Heading	Thermal sensitive 35 days (500°C units)
Intermediate	Photoperiod-thermal sensitive 40–70 days (600°C–750°C units + day length)	Panicle initiation	Thermal sensitive 21 days (300°C units)	Heading	Thermal sensitive 35 days (500°C units)
Late	Photoperiod sensitive 30–90 days (day length)	Panicle initiation	Thermal sensitive 21 days (300°C units)	Heading	Thermal sensitive 35 days (500°C units)

8. Phenology drivers for early, intermediate, and late maturing rice cultivars.

Phenology delay is one of the major impacts of stress. It has been found, for example, that moisture stress will increase the length of time to panicle initiation, probably via a slowdown or stoppage in the hormone accumulation process. When the moisture stress is removed, hormone accumulation (and thus rice development) begins again. "Shock effects" are also experienced from temperatures outside the favorable range. Indeed, stress impacts on phenology can vary significantly in direction and magnitude and both direction and magnitude can vary with the stage of development when the stress is applied.

The entire rice crop grown in a grid cell is not developing at the same rate. When one culm is undergoing a particular stage of development, it is unlikely that the culms next to it are in the same stage of development. This creates a spreading phenomenon that is important when assessing environmental parameters which manifest their effects at specific points in plant development.

The phenology model uses temperature and daylength information to determine "baseline" stage(s) of development for the rice grown in each grid cell. This baseline is adjusted, as appropriate, for the impacts of stress and interpreted in terms of % of crop at each stage of development.

Meteorological variances model

Model interactions are related to the model's basic function as a convergence of evidence type information generator. Its yield estimates go directly to the analyst responsible for yield determination and prediction.

Model operation is based on the procedure of making crop inferences by comparing the present growing season's environmental parameters with those of past seasons. Meteorological variables such as temperature, rainfall, and wind velocity are compared with historic means; variances and abnormalities are flagged as causing potential yield impact. YIA involves examinating the magnitude and duration of deviations at the stage(s) of crop development where the deviation occurred. If flags are not raised, then the yield estimates are derived from multiple regression analysis.

The meteorological variances model uses mean yields with a trend term as discussed in the yield reduction model. In this case mean yield becomes a measure of background influences on yield. The advantage of the variances model approach is that if any weather parameter is abnormal, as defined by meteorological variance, then the analyst is alerted to a possible major influence on yield. The yield reduction model uses specific meteorological values which, if correct interpretors of yield change, result in accurate yield estimates. If the values are not correct, the variances model flags a potential yield modification. For example, a 24°C temperature at heading may be an abnormal occurrence and may well reduce yield but would not be evaluated in the yield reduction model. Verification of yield impact by this method would lead to modification of the meteorological values used in the yield reduction model.

Analyst evaluation

Yield models are only tools. Man must interpret the model estimates and determine the confidence level of the results. He can then make a yield prediction at some confidence level. The rice yield model discussed here uses a convergence of evidence approach, so that an analyst can make a more reliable yield estimate. The model also flags the main factors influencing yields so the analyst can troubleshoot if something appears wrong.

Confidence levels can be added to the data stored within the data base. Then a confidence level factor can be generated along with the yield estimates. For example, if the meteorological data for a cell are generated by a spreading program because there are no meteorological data for that cell, the confidence level in the yield estimates will be lower. If the cell has a large variance in topography, then the confidence level of the data may be further reduced. This provides the analyst with a reliability factor that can be taken into account in his final yield prediction. Success in yield predictions from the model allows the evaluation of factors limiting yield in a cell. Research can then be brought to bear to reduce the impact of the limiting factors.

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Dynamic simulation of irrigated rice crop growth and yield

J. A. McMennamy

The development of a relatively simple rice population model called RICEMOD which is driven by (or is responsive to) daily weather parameters is discussed. The model is based on selected functional relationships found in rice research literature. The model's accuracy is assessed and potential uses are suggested.

Functional relationships within economic, engineering, and biological systems are often difficult to evaluate because of the systems's complexicity. Numerical modeling has proven to be a useful research tool to assess the researcher's understanding of the system or to test the validity of suggested cause and effect relationships.

In the plant sciences, crop modeling is often used to inventory and test hypothetical plant performance relationships, and assess the effects of environment on plant performance. In instances where several performance relationships exist, a model can be used to rationalize or resolve conflicting hypotheses about cause and effect relationships. If the model accurately predicts plant growth in most cases, it is considered a "good model," and may help identify research areas with the greatest potential to improve plant performance. Cases in which the good model does not agree with actual plant growth are of particular interest to plant physiologists and indicate a need for additional research to better understand and define plant behavior.

This paper describes the initial efforts to develop a relatively simple rice plant population model called RICEMOD, which is driven by (or is responsive to) the daily weather parameters: solar radiation, maximum and minimum temperatures, and day length. The accuracy of the model is assessed and potential uses are suggested. The model is based on selected functional relationships found in rice research literature. The validity and precision of these relationships is not beyond question; hence, the inaccurate performance of the model is not totally unexpected.

MODEL DESCRIPTION

The ultimate rice crop growth simulation model should be simple yet comprehensive enough to predict the growth of different varieties under any agroclimatic condition. RICEMOD is far from the ultimate and several major simplifying assumptions have been made:

1. The crop is irrigated and water stress does not limit its growth.
2. The crop is treated as a homogenous plant population of transplanted IR36, an IRRI improved variety.
3. Luxury levels of plant nutrients are present.

The processes of photosynthesis, respiration, and the partitioning of assimilate are dynamic with respect to changes in environmental factors and plant development. In RICEMOD, as in a growing rice plant, photosynthate is produced by the irradiation of leaves. The net amount of photosynthetic product generated is influenced by light intensity, leaf area, canopy shape, leaf thickness, and the nitrogen content of the leaf blades. After part of the photosynthate is used for growth respiration, the remainder is distributed to the roots, the culm and leaf sheath, the leaf blades, and, after the vegetative stage, the panicle. Maintenance respiration continues at night and results in some dry matter loss.

Figure 1 is a schematic of the RICEMOD system and illustrates how the model simulates growth through a series of incremental computations. A day is considered to start at sunrise and end at sunrise on the following day. The net carbon dioxide exchange rate is

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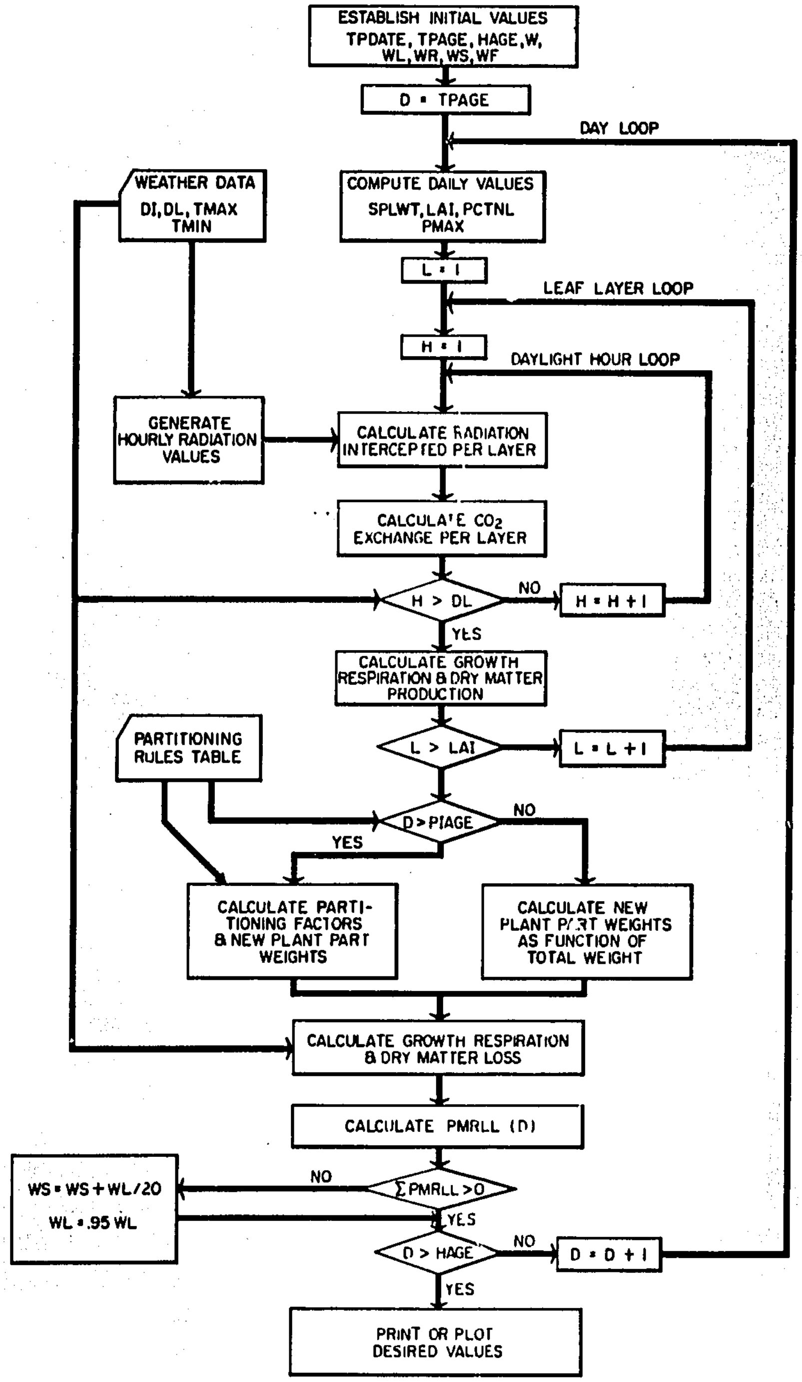


1. Schematic of the RICEMOD growth simulator. D = plant population age (d); DI(D) = daily total PAR on day D (cal/cm^2); DL = day length (h); FL, FS, FR, FF = fraction (g/g) of photosynthate partitioned to panicles (F), leaf blades (L), culm and leaf sheath (S), and roots (R); H = hour of the day (H = 0 at sunrise) (h); HAGE = plant age at harvest (d); L = leaf layer (the top layer is layer 1); LAI = leaf area index, m^2/m^2; PCTNL = percent nitrogen content of leaves (g/g x 100); PIAGE = plant age (d) at panicle initiation; PMAX = maximum daytime net CO_2 exchange (g/m^2 per h); PMRLL = daily net CO_2 exchange (g/m^2) for lowest leaf layer; PT(D) = total net CO_2 exchange (g/m^2) during daylight hours of day D; SPLWT = specific leaf weight (g/m^2); TMAX = max daily temp (°C); TMIN = min daily temp (°C); TPAGE = age (d) of plants at transplanting; TPDATE = transplanting date; W = total wt of plant population (g/m^2); WF, WL, WR, WS = dry wt (g/m^2) of panicle, leaf blades, roots, and leaf sheath and culm.

calculated each daylight hour for each layer of leaves, and can be repeated more than 100 times/day during the middle of the growing season. This number of calculations would be impractical without a computer. RICEMOD has been programmed in FORTRAN IV and BASIC. The FORTRAN program requires about 20 seconds of computer time/crop (after compilation) when run on an IBM 370/135 computer.

FUNCTIONAL RELATIONSHIPS

Photosynthesis has been studied extensively. Researchers have produced evidence that the photosynthetic rate of plants is significantly influenced by light intensity and spectra, leaf area, leaf canopy structure, plant species and variety, chemical content of the leaf, temperature, wind speed, plant water status, and air chemistry. In RICEMOD, photosynthesis is treated as the process whereby atmospheric carbon dioxide is fixed by the plant. The process rate is a function of photosynthetically active radiation (PAR) in the 400 to 700 mm waveband incidence per unit leaf area. The function is assumed to fit the rectangular hyperbolic curve described by the following equation (McDonald 1971):

$$P = \frac{1}{\frac{1}{PMAX} + \frac{1}{\gamma I}}, \qquad (1)$$

where: I = hourly PAR (cal/cm^2),
P = hourly carbon dioxide exchange rate ($g\ CO_2/m^2$),
$PMAX$ = max hourly carbon dioxide exchange rate ($g\ CO_2/m^2$) as I approaches infinity, and
γ = initial slope of the response curve.

McDonald showed that the initial response curve slope (γ) varies with temperature and variety, but it is assumed to be constant in RICEMOD because the changes are relatively small.

Takano and Tsunoda (1971) and Yoshida and Coronel (1976) have shown that the major variations in *PMAX* can be related to changes in leaf nitrogen content. RICEMOD employs a relationship suggested by Yoshida:

$$P_{60} = 2.6\ AWNL, \qquad (2)$$

where: P_{60} = the net photosynthetic rate (g/m^2 per hour) at 60 klux (21.6 $cal/cm^2/h$) irradiance, and
$AWNL$ = the ratio of leaf nitrogen weight to leaf area (g/m^2). *PMAX* can be derived by substituting P_{60} in equation 1.

The areal leaf nitrogen content (*AWNL*) is a function of specific leaf weight (*SPLWT*) and the percent nitrogen content of the leaves (*PCTNL*). In RICEMOD, both parameters are treated as functions of plant age alone. Although environmental factors have an influence, specific functional relationships were not found in the literature reviewed.

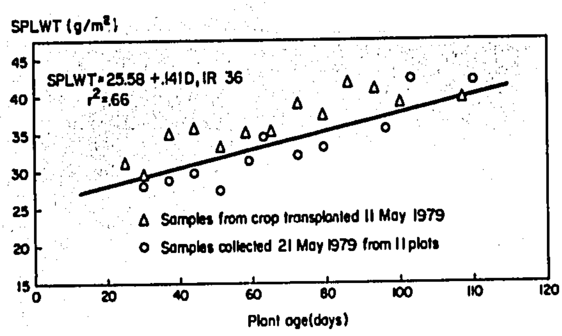
Data supplied by Puckridge and Haws (Fig. 2, 3) on IR36 were used to establish the *SPLWT* and *PCTNL* functions:

$$SPLWT = 25.6 + .141D, \text{ and} \qquad (3)$$

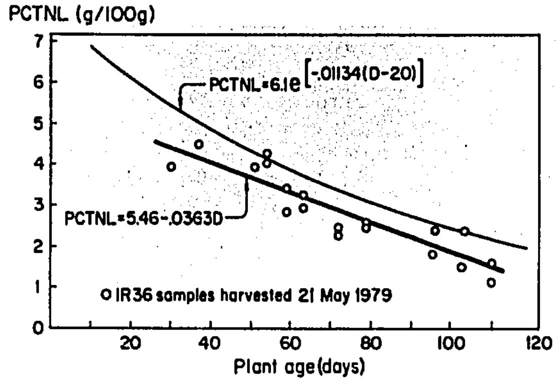
$$PCTNL = 5.465 - .0363\ D, \qquad (4)$$

where: D = the age (days) of IR36 plants.

To determine the total amount of carbon dioxide fixed per day, the light intercepted by each layer of leaves must be determined (I in equation 1). Hourly radiation $I(D, H)$ is derived from daily radiation using a method suggested by Arkin et al (1978). This method uniformly distributes the daily PAR value under a sinusoidal distribution curve which is symmetric about solar noon.



2. The RICEMOD functional relationship between plant age (D) and specific leaf weight (SPLWT). Data for IR36 were supplied by D. W. Puckridge (personal communication).



3. The RICEMOD functional relationship between plant age (D) and percentage nitrogen in the leaf blades (PCTNL). The relationship developed by Murata (1975 light line) is shown for reference. Data for IR36 were supplied by D. W. Puckridge (personal communication).

Realistic values are expected in the dry season, but a non-uniform radiation distribution is expected during the monsoon season. Further study of weather records is needed.

The random distribution canopy model used by Curry (1971) and Curry et al (1975) for soybean and corn was adapted for RICEMOD. This Montieth-type model is based on a series function of light interception by successive leaf layers. For example, a leaf canopy with a leaf area index (LAI) of 3.4 is treated as 4 horizontal layers - 3 full layers and a bottom layer with a 0.4 m^2 per m^2 of ground area. The top layer is exposed to full radiation but, a fraction (*S*) passes through the layer without being intercepted. The value of *S* is dependent on canopy architecture. Curry used a value of .64 for the flat (planophile) leaf structure of soybean. The more erect leaf arrangement of corn received a value of .5. Thus, the radiation intercepted by the topmost layer *I(D,H)* is $\{(1-S)(1-T)\}$, where *T* is the transmission coefficient. In RICEMOD, the term $\{(1-S)(1-T)\}$ is called the *attenuation factor (AF)*. The radiation intercepted by any layer (*L*) can be expressed:

$$I(D,H,L) = I(D,H)\ AF\ (1-AF)^{L-1} \quad (5)$$

The net daily carbon dioxide exchange rate during daylight hours can be found by solving equation 1 for each layer for each hour of the day.

Respiration is related to plant growth and metabolism. RICEMOD uses the concept suggested by McCree (1974), in which growth respiration is treated as a function of photosynthetic activity, and maintenance respiration is a function of temperature and total plant weight. Respiration rates of various plant parts differ and the differences change as the plant matures (Hesketh et al 1971, Yamaguchi 1978). The model is constructed so that respiration rates can be treated as independent variables for different plant parts. At the present level of model development, however, respiration rates are held constant. The RICEMOD growth function includes the effects of growth respiration and has the form:

$$PLUSW(D) = PT(D)\{1 - RG\}/1.43 \quad (6)$$

where: *PLUSW(D)* = dry weight added on day $D (g/m^2)$,
PT(D) = net carbon dioxide exchange rate (g/m^3) during daylight hours of day *D*,
RG = growth respiration coefficient (g/g),
1.43 = factor for converting dry weight to an equivalent weight of carbon dioxide.

Metabolic reactions continue at night until the substrate reserves produced during the daylight hours are exhausted. Beyond this point, further carbon dioxide is lost only to maintenance requirements. McCree points out that both growth and maintenance respiration occur during the day and night hours. This seems reasonable based on the results of his experiments, but to simplify RICEMOD, growth respiration is treated solely as a tax on photosynthesis (equation 6). The dry matter weight lost to maintenance respiration at night is determined for each plant part as follows:

$$WL(D) = \{WL(D-1) + PLUSWL(D)\}\{1-(RM)(TC)(\frac{24-DL(D)}{12})\} \quad (7)$$

where: *WL(D)* = leaf blade weight at end of day *D*,
WL(D-1) = leaf blade on the previous day,
PLUSWL(D) = weight added to leaf blades on day *D*,
RM = maintenance respiration coefficient,
TC = temperature coefficient.

Similar equations are used for the culm and leaf sheath, roots, and panicles. McCree's temperature coefficient (*TC*) is found with the use of average night temperature:

$$NT(D) = TMIN(D+1) + \frac{TMAX(D)-TMIN(D+1)}{4}, \quad (8)$$

and McCree's equation:

$$TC = .044 + .0019NT + .0010NT^2, \quad (9)$$

where: $NT(D)$ = average night temperature (°C) on day D,

$TMIN(D+1)$ = minimum temperature (°C) on next day,

$TMAX(D)$ = maximum temperature (°C) on present day.

Equations 7, 8, and 9 are solved once per day. Because the weight lost per day to maintenance respiration is relatively small compared to the weight gained, and because daily temperature fluctuations are normally small in tropical rice-growing areas, a daily maintenance respiration weight loss was computed to reduce computation time.

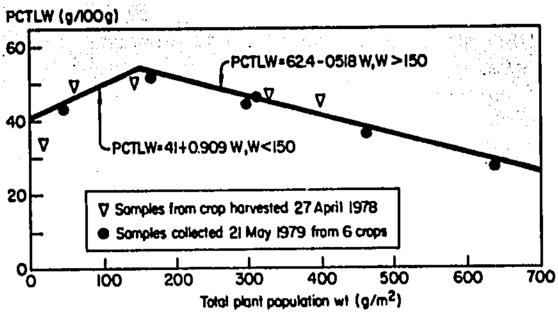
The partitioning to the various plant parts of assimilates produced by photosynthesis ultimately decides crop growth and yield. Some plants exhibit adaptive mechanisms whereby the partitioning of assimilates is adjusted to help the plant cope with an abnormal environment. For example, some species and varieties will develop a more extensive root system in dry conditions than in wet, and some rice varieties will develop longer internodes when exposed to deep water than when grown in shallow water. The state-of-the-art knowledge about these adaptive mechanisms seems more qualitative than quantitative; thus development of the partitioning part of the model is very challenging.

RICEMOD uses two approaches to modeling plant development; one is used exclusively during the vegetative growth phase and the other after the reproductive phase begins.

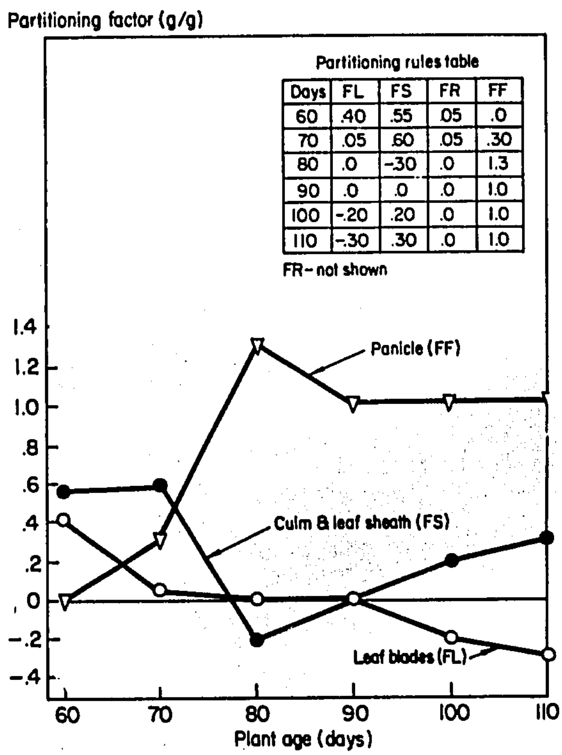
During the vegetative phase (prior to panicle initiation), plant growth in RICEMOD is governed by an "architectural standard." Figure 4 shows the percentages of leaf weight versus total weight for several IR36 crops grown at different times of the year. Based on the consistency of this relationship, it is assumed that the relative percentages represented by the culm and leaf sheath, leaf blades, and roots is a function of the total population weight per unit area.

Monsi and Murata (1969) developed a "distribution factor" concept, which was adapted to regulate plant growth after panicle growth starts. As the plant develops, the distribution factors are changed by interpolating between points specified in a "partitioning rules table" (Fig. 5). As more quantitative information about adaptive growth functions becomes available, the RICEMOD program can treat values in the partitioning rules table as variables, but they are currently assigned constant values.

If the daily CO_2 exchange is negative in the lowest leaf layer, it is assumed that further leaf



4. The RICEMOD functional relationship between plant age (D) and percentage leaf blade weight (PCTLW). Data for IR36 were supplied by L. D. Haws and D. W. Puckridge (personal communication).



Days	FL	FS	FR	FF
60	.40	.55	.05	.0
70	.05	.60	.05	.30
80	.0	-.30	.0	1.3
90	.0	.0	.0	1.0
100	-.20	.20	.0	1.0
110	-.30	.30	.0	1.0

5. RICEMOD partitioning rules table and graphic representation of partitioning factors (F) derived by interpolating between values in the table. IR36.

growth is unnecessary. To smooth the effect of one unusual day, RICEMOD maintains a running 3-day balance on net carbon dioxide exchange in the lowest layer. If the 3-day balance becomes negative, 5% of the leaf weight is transferred to the stems. It is important to note that this redistribution of leaf material is superimposed on the partitional process and exerts a gentle correcting effect on plant development without completely replacing the model's basic control mechanism - the partitioning rules table.

MODEL OUTPUT

To use the model, coefficients must first be selected for the functional relationships. Several of the required coefficients, derived empirically, have been described previously. In the absence of measurements on IR36, some coefficients were assigned values.

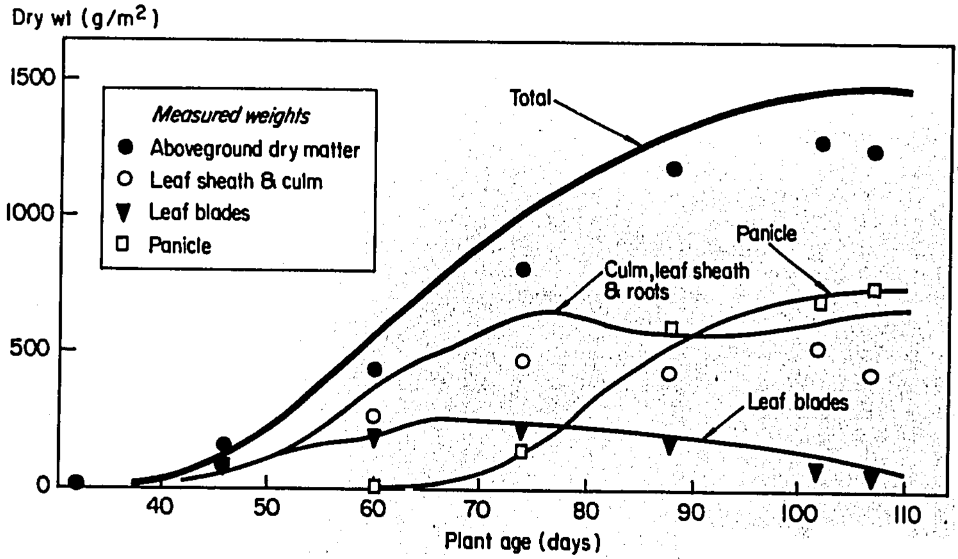
The attenuation factor (*AF*) was given a value of .52, which gives the model a reasonable response. However, a lower value would agree better with measurements of extinction coefficients for rice varieties with erect leaves (Uchijima 1976).

The growth respiration coefficient (*RG*) was assigned a value of .28 g CO_2/ g CO_2, and the maintenance respiration coefficient (*RM*) was given a value of .017 g/g of dry matter. These values are within the range found in the literature (Penning de Vries 1975). More exact information is needed on how the values are influenced by variety, plant part, and plant age.

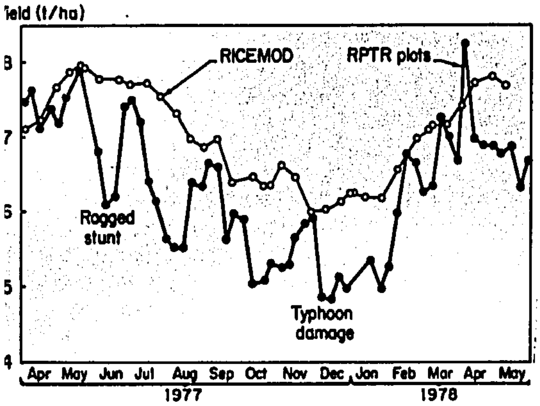
To test RICEMOD's ability to predict IR36 development, weather data supplied by IRRI's Agroclimatic Service Unit were used to produce the curves shown in Figure 6. The growth curves can be adjusted by changing the values in the partitioning rules table. They presently agree reasonably well with field measurements and the expected harvest index, time of maximum leaf area development, and shape of the total dry matter accumulation curve (Angus 1979).

The yields predicted by RICEMOD were also compared with field yields obtained over a 1-year period. The IRRI department of Rice Production Training and Research (RPTR) has an ongoing experiment in which IR36 is continuously planted and harvested (Morooka et al 1979). Figure 7 shows the maximum weekly yield harvested from the RPTR plots at the IRRI experimental farm in Los Baños. Using IRRI's weather data, RICEMOD yields closely tracked the field yields except in periods of low yield because of disease, rat damage, or typhoons.

Yoshida and Parao (1976) conducted a series of experiments to determine the effects of shading at different growth stages on the yield of IR747-B2-6, a variety that matures in 96 days. To compare the yield predicted by RICEMOD with the experimental results, several adjustments were made:



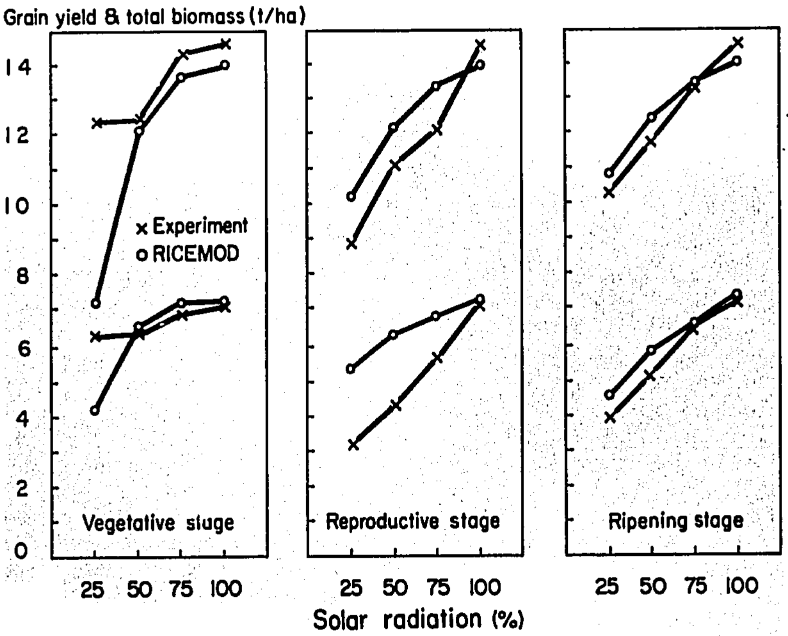
6. Total dry weight and plant part dry weights predicted by RICEMOD for IR36 harvested 17 May 1978. Measured weights are from IRRI Plant Physiology Department data.



7. Comparison of maximum weekly yield of IR36 in RPTR plots (Morooka et al 1979) and yields predicted by RICEMOD.

1. Plant weight at transplanting was increased 35% to compensate for the higher seedling population used in the experiment compared to that used in the RPTR plots.
2. Panicle initiation in IR747-B2-6 occurs at about 45 days, so the "architectural standard" that regulates growth in RICEMOD was discontinued at 46 days.
3. The time scale in the partitioning rules tables was shortened to reflect the earlier flowering and maturity dates of IR747-B2-6, and the panicle partitioning factor was reduced about 10% because early-maturing varieties are thought to translocate less assimilate than late-maturing ones.
4. The attenuation factor was assigned a value of .58.
5. Actual weather data were not readily available, so constant values were used: $I(D)$ = 475 cal/cm^2, $TMAX$ = 31.5°C, $TMIN$ = 22.6°C, and day length = 12.9 hours.

RICEMOD closely predicted the yield reduction due to shading during the grain-filling period (Fig. 8), but full reduction was not predicted in the reproductive stage. Yoshida and Parao (1976) hypothesized that the main cause of yield reduction at this stage is the pronounced reduction of spikelets. The maximum number of grains is fixed at the end of this stage, and an abundant assimilate supply during grain filling can do no more than fill grains that are more or less fixed in number and size, something RICEMOD does not account for.



8. The effect of reducing solar radiation at different growth stages on the total biomass production (upper curves) and grain yield of IR747B2-6. Experiment data from Yoshida and Parao (1976).

The yield reduction predicted at 25 and 50% shading during the vegetative stage agreed with the experimental results, but greatly different results were obtained at 75% shading. One hypothesis is that because of light reflected from the paddy water surface, the plant in the field receives higher radiation than predicted. Under higher radiation, the plant develops its canopy quickly and this effect is not expressed. With very low radiation, canopy development takes much longer and this effect could become significant.

CONCLUSION

Limited experience with RICEMOD indicates that reasonably accurate results can be expected using daily weather data, but a more sensitive model may require hourly values, especially if diurnal fluctuations are irregular.

RICEMOD can be used to study the relative effects of radiation, leaf blade nitrogen content, respiration rate, and assimilate partitioning on rice plant growth. To accurately predict growth, more information is needed on respiration and the environmental effects on nutrient uptake and distribution, leaf blade thickness, and the plant growth control mechanism. The model would be more useful if it were sensitive to water and nutrient stresses.

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Rainfall recurrence analysis for extrapolating rice-based cropping patterns

R. A. Morris and F. M. Rumbaoa, Jr.

Rainfall variability during monsoon transition periods appears critical to the intensification of cropping systems. Techniques to analyze locational similarity and annual variability of transition rainfall are described. The former use simple regression methods to determine similarities between paired stations, and the latter use return period analysis to determine the recurrence probabilities of pre-selected three-day rainfall totals during critical intervals in the cropping season.

The techniques used to analyze rainfall data during the transition periods are sufficiently simple for use at research site field offices to make initial approximations of cropping pattern adaptation areas.

In South and Southeast Asia, monsoon rainfall is the major water source for many small farms where rice is the major crop. Because of their agricultural effects on farm operations, monsoon onsets, and to a lesser extent, retreats and interruptions have been examined for many locations (Huke 1966, Kao and Hsu 1962, Morris and Zandstra 1979, Sastry 1976, Raj 1979). A range of 4 to 5 weeks appears typical for locations where extreme onset dates have been examined. For Southeast Asia, Orgill (1967) found a range of 33 days about a mean onset date of 17 May using abrupt fracture of the equational shear line which allows equatorial westerlies to penetrate northward as the onset criterion.

In rainfed agriculture and in many partially irrigated areas, monsoon advances and retreats determine the length of the growing season. Ramage (1971) discussed the advance and retreat transition periods for various areas. Rainy days in these transition periods appear to be dominated by "showers" as opposed to "rains." Huke found that the amount of rain on the first day of the wet monsoon averaged only 60% that of any other rainy day. For 8 Philippine stations directly exposed to the equatorial westerlies, a rainy day in May received only 66% as much rain as a rainy day in August. Rainy days during the wet-dry season transition (October and November) received only 61% of the rain of an average rainy August day. Similar differences may exist elsewhere.

The rice-based cropping systems research programs in many countries within monsoonal South and Southeast Asia have predominantly focused on rainfed and partially irrigated cropping patterns suitable for small farmers (IRRI 1979). In many of these programs, the agronomist must develop management practices that will make intensified cropping patterns relatively stable regardless of weather extremes. Although he has identified the onset and retreat periods through experience or rainfall record analysis, he knows that four 6 to 10 mm showers do not equal one 32 mm shower because much of the rain from light showers rapidly evaporates. Heavy showers during transition periods greatly influence the rate of change in soil moisture. Both recharge and drainage are critical to crop adaptation in the transition period and determine the soil management practices required to grow a crop successfully.

Once crop adaptation and soil management studies are under way at a cropping system site, two questions arise: How will the practices perform in other years? How will they perform on farms 100 km from the main study site? Crop modeling techniques can provide insight into the performance of patterns in other years

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and at other places, but modeling has little to offer the immediate needs of field researchers, given the present state of the art. Interim analytical techniques are needed.

This paper discusses analytical techniques for examining meteorological events critical to the performance of rainfed and partially irrigated rice-based cropping systems. Many of the techniques used in this study are discussed more fully by Jackson (1977) and Viessman et al (1972). For application of the techniques both the critical interval on the crop calendar and the determining meteorological variable must be correctly identified. This paper focuses on rainfall, but the techniques could be applied to other critical weather attributes.

We know from mean monthly rainfall studies that similar rainfall patterns exist over the northern portion of the Central Luzon Valley in the Philippines, which encompasses major portions of Pangasinan, Tarlac, and Nueva Ecija provinces. How similar are these patterns in attributes other than mean monthly rainfall? Rainfall records from several stations in this area were compared for similarities in what are assumed to be critical attributes. The intervals were chosen on the basis of their importance to the performance of 2 cropping patterns studied for 4 years in Manaoag, Pangasinan. The objective of our analysis was to identify the area over which results from a cropping systems program could be extrapolated.

SPATIAL SIMILARITIES OF DRY-WET AND WET-DRY TRANSITION RAINFALL

Cropping activities in the study area are strongly affected by monsoon rainfall patterns, and the dates of wet monsoon onsets and terminations. Procedures for determining empirical probabilities from long-term rainfall series have been developed for cropping systems studies (Morris and Zandstra 1979). Questions arise, however, about extrapolating the probabilities of rainfall over even relatively short distances, given the strong spatial gradients in rainfall distributions caused by differences in surface features.

The number of rainfall observation stations in the study area was increased 5 years ago in recognition of *spatial variability*. Although record lengths were extremely short for most analytical purposes, comparisons of rainfall totals for sequential 10-day intervals during the transition periods should provide a basis for preliminary *judgments* about extrapolation. The similarity of rainfall patterns over distance during the transition between the dry and wet monsoons (April to June) and between the wet and dry monsoons (October to December) were of most interest. Showers during these periods are the commonest type of precipitation, and it is assumed that the spatial distributions of these showers are influenced by surface factors, principally proximities to bodies of water (including extensive areas of irrigated land) and major physiographic features.

RETURN PERIODS OF CRITICAL VARIABLES

The dry-wet transition period

Rains sufficiently heavy to infiltrate about 25-30 cm are needed to establish dry-seeded rice[a] successfully. A moist plow layer is required to reduce draft requirements, to improve the tilth of plowed land, to obtain complete and uniform emergence, and to sustain early seedling growth. A sequence of three days or less of moderate rainfall during the dry-wet transition will produce a moist soil surface. Isolated light rains do not infiltrate the soil profile, but quickly evaporate if much heat has been stored in the soil surface during intervening dry periods. Assuming that 60-70% of rain during a 3-day period in which at least one heavy shower occurred would infiltrate the soil, a rainfall total of 50 mm/3-day period was set as the lower criterion that would provide sufficient moisture for germination of rice and about 10 days of initial growth. If root growth reaches 30 to 40 cm and moisture (even of low availability) is present, a rice crop can be maintained in a dormant state for several weeks. Inasmuch as rainfall outside the 3-day period is not considered, the criterion of 50 mm/3 days is assumed to be conservative.

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[a]Dry-seeded rice is a crop which has been sown directly on the field before the soil is saturated or flooded. Early growth occurs before rains become sufficiently heavy to maintain a flooded state. The soil is not puddled. The rice is called *aus* rice in Bangladesh, *gogo-rancah* in Indonesia, *sabog-tanim* in the Philippines, and *kaonum* in Thailand.

Because it was difficult to discriminate between occasional periods of heavy showers in an otherwise dry period and a few days of heavy rains in a protracted rainy period, and too risky to assume the latter, no upper limit was established. Such a limit, if exceeded, would have indicated too much rain had fallen for "dry" plowing, harrowing, and seeding operations.

The wet-dry transition period

The distribution of major rainfall events during the wet-dry transition period are of interest for three reasons. First, where a second rice crop or ratoon crop is attempted in low-lying fields, runoff and interflow from higher fields will be most significant from heavy rains which recharge the fields. Light and moderate rains will wet only the surface soil of the higher and drier fields, and contribute little to lower fields. Second, heavy rains which fall between planting and early vegetative development accentuate seed rot, damping-off disease, and excessive moisture injury. Third, one or more light to moderate rains during an otherwise dry planting period will promote emergence.

A few light rains over a short period improve emergence percentage and uniformity during emergence. One 25 mm shower would moisten the surface soil of a plowed field to 20 cm, assuming a net infiltration of 20 mm was stored at about 0.1 cm water/cm soil. On the other hand, a series of moderate to heavy rains in a 3-day period would increase the chances of seed rot if emergence has not occurred, damping off during the seedling stage, and excess moisture injury during early vegetative stages. By assuming that only 25 mm could be safely stored in the 0-30 cm layer, 20 mm could be stored in the 30-50 cm layer, that there would be no significant infiltration below 50 cm, and that 5 mm would be lost by ET each day of the 3-day period, any rainfall above 100 mm/3 days would have to fill macropores or be stored on the surface, leading to crop damage. As criteria for the late wet monsoon period, 25 and 100 mm/3 days have been used, where the former is a level set in view of moisture requirements for emergence and the latter is set in view of the damaging effects of a brief period of heavy rains on a soil that is partially depleted in the root zone but near saturation below 50 cm.

ANALYTICAL TECHNIQUES

Short-term rainfall records from 18 observation stations in the study area were used to determine the similarity between rainfall patterns. To compare stations with Manaoag, we assumed that if factors causing transition period disturbances were similar over the area, rainfall totals would also be similar but rainfall would not necessarily occur on the same day or even within a period of 2 or 3 days. Much of this rain would be generated through cumulonimbus cloud development.

Two regression models were used.

$$Yij = b\ Xij$$

$$Yij = b_i\ Xij$$

where, Xij was rainfall at Manaoag in the jth period of the ith year, and Yij was rainfall at the paired station for the corresponding period and year. In the first model, similar transition behavior was assumed appropriate over years, but in the second, the model allowed for differences in behavior between years, and therefore 4 regression coefficients were determined. Preliminary computations using models with intercept terms showed that the intercepts were generally not significantly different from zero. Rainfall for 8 successive 10-day periods, starting with 1 April were combined over 4 years for the dry-wet regression model. The coverage was limited because only 4 years of data were available for Manaoag and, in most cases, only 4 years were available for other stations. Daily rainfall records were obtained from stations operated by the National Irrigation Administration; the Philippine Atmospheric, Geophysical, and Astronomical Services Administration; and Central Luzon State University.

The simple regression model computed b and R^2 between Manaoag and other stations, with Manaoag as the independent variable. The b's were regarded as indicating average correspondence between rainfall totals and the R^2's were regarded as indicating the dispersion of the totals. On the basis of b and R^2 from the dry-wet transition model, the area was divided into two sections: one similar to Manaoag and the other "different". A similar division was made on the basis of the wet-dry transition model. To compare the results of this simple but subjective method with a more comprehensive and objective approach, the b_i's and R^2's from the second regression model were subjected to cluster analysis (Barr et al 1976). Four clusters were determined for the dry-wet and wet-dry transition periods, and the study area was divided into sections similar and different to Manaoag for each period. In the cluster analyses, the b_i's rather than b's were used because we assumed the coefficients for individual years would capture more of the similarities within years.

Long-term rainfall records from Cabanatuan City (1950-78) and Dagupan City (1949-75) were used to determine approximate probabilities for key transition period and mid-wet monsoon variables. Probabilities were calculated from the Weibull plotting formula:

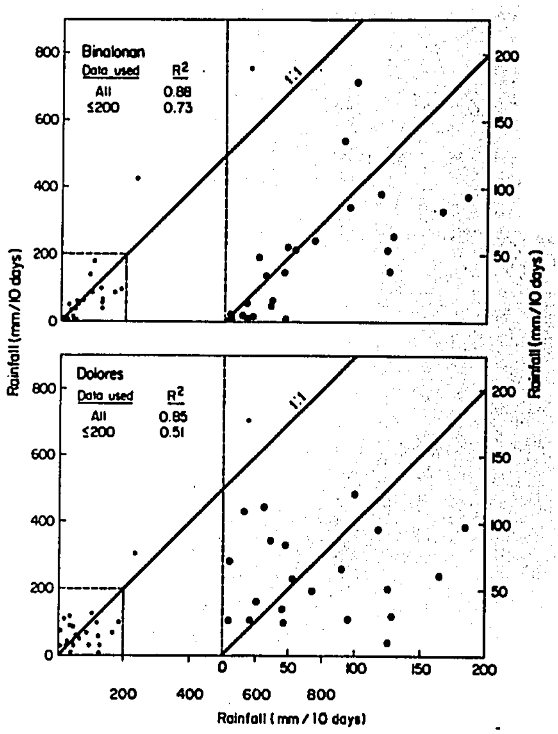
$$W = \frac{m}{n + 1}$$

where, the return period is equal to the inverse of W, m is the rank of the observation (in descending order), and n is the number of years of observations. Routine plotting procedures were followed to construct return period diagrams.

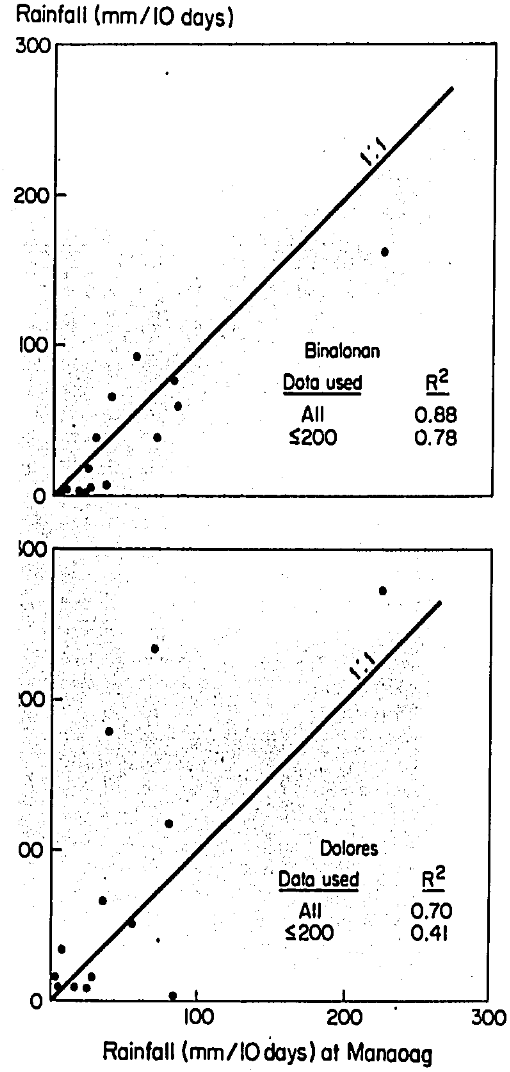
RESULTS AND DISCUSSION

Spatial similarities

The scatter diagrams in Figure 1 show that for both a close station (Binalonan) and a distant station (Dolores), R^2 was high when all rainfall was included, but decreased, especially for the distant station, when all periods with rainfall greater than 200 mm were excluded.



1. Scatter diagrams of dry-wet transition period rainfall at Manaoag and two contrasting stations, and R^2 for $Y_{ij} = bX_{ij}$ using deleted and undeleted rainfall data. All data points on left hand; only ≤200 mm data points on right-hand scale.



2. Scatter diagrams of wet-dry transition period rainfall at Manaoag and two contrasting stations, and R^2 for $Y_{ij} = bX_{ij}$ using deleted and undeleted rainfall data.

Periods with rainfall greater than 200 mm were dominated by tropical depressions and, although there were few during the 32 periods considered, the wide coverage of these typhoon systems resulted in a higher R^2. Because focus was placed on differences in transition period rainfall that presumably arose from localized land surface-atmosphere differences, only period pairs with less than 200 mm were considered for defining areas with similar weather patterns.

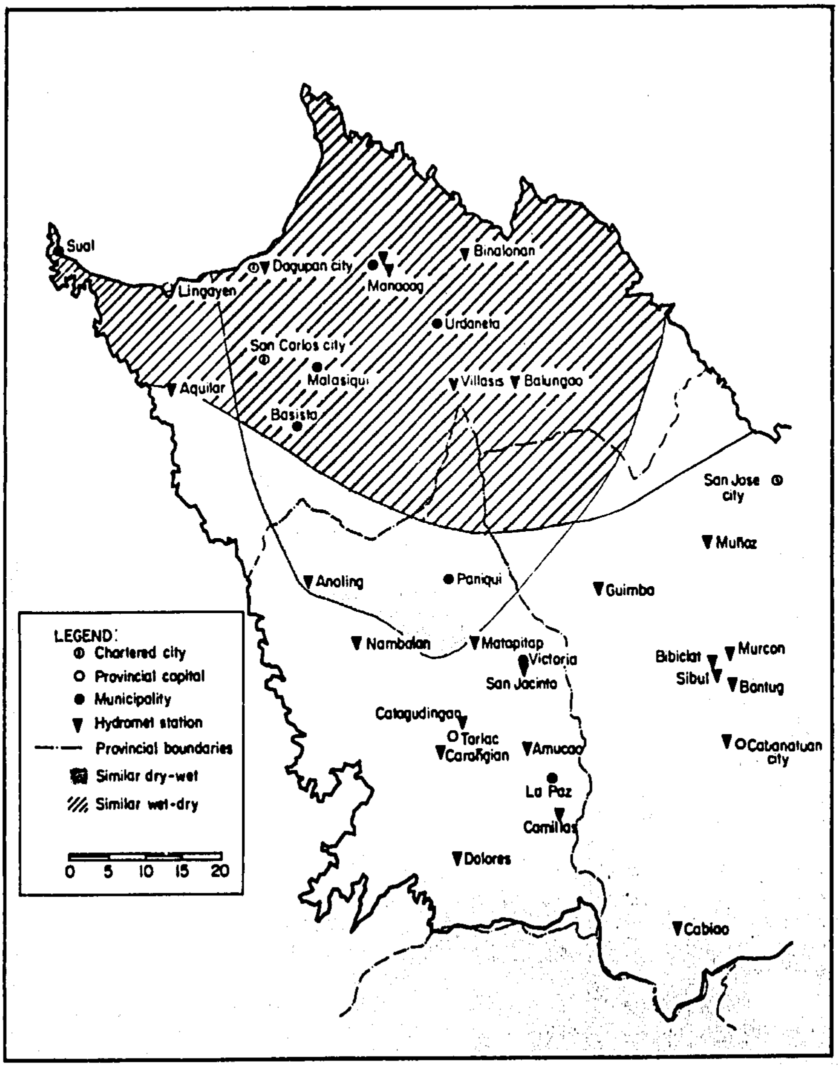
As in the dry-wet transition analysis, R^2 was reduced when only period pairs with $\leq$200 mm rainfall were used in wet-dry transition analysis. Scatter diagrams for Binalonan and Dolores illustrate the effect of distance

Table 1. Criteria for station classification.

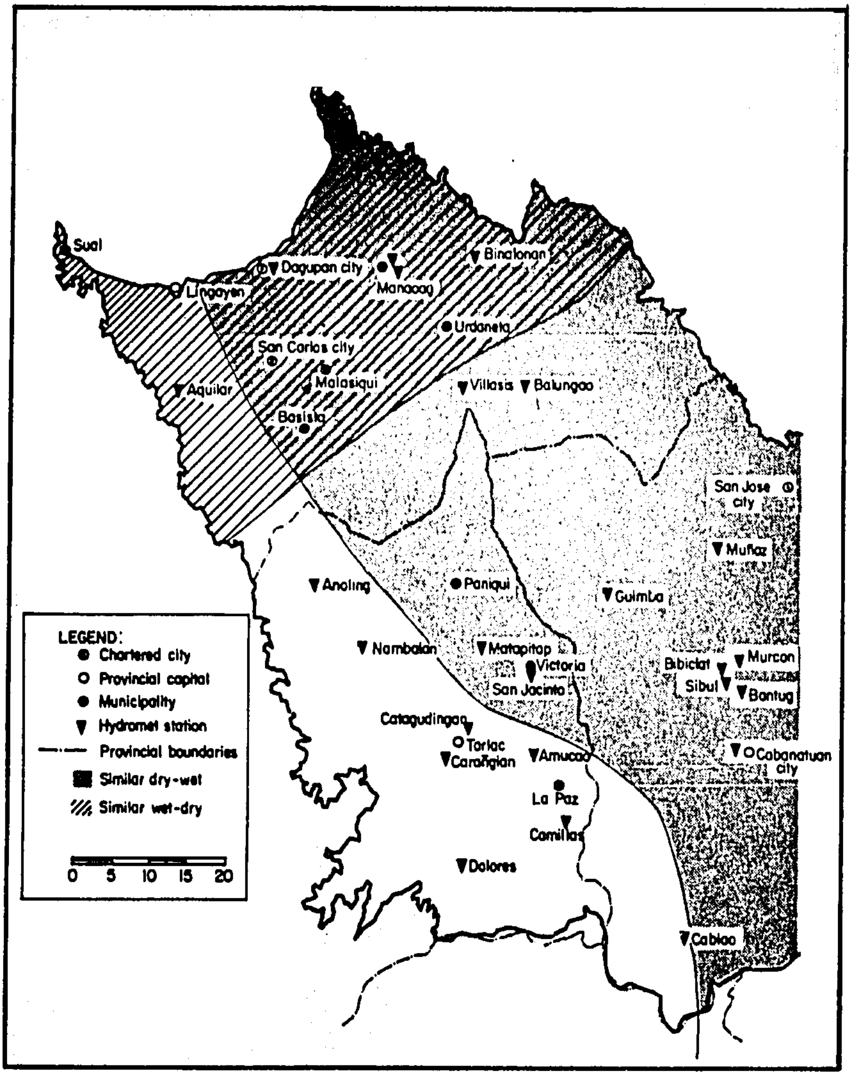
Class	Statistic	Value Dry-wet	Value Wet-dry
Similar	b	$\geq$0.67	$\leq$1.35
	R^2	and	and
		$\geq$ 55	$\geq$ 65
Different	b	$\leq$0.50	$\geq$1.50
		or	or
	R^2	$\leq$ 45	$\leq$ 50

(Fig. 2). Inspection of one-to-one scatter diagrams, however, showed stations to the south to have generally higher rainfall during the wetter periods. A decrease in R^2 with distance was also found for the wet-dry transition.

The criteria given in Table 1 were



3. Areas similar and different with respect to Manaoag during the dry-wet and wet-dry transitions, determined on the basis of R^2 and b from $Y_{ij} = bX_{ij}$.



4. Areas similar and different with respect to Manaoag during the dry-wet and wet-dry transitions, determined by cluster analysis.

used to classify stations as similar or different to Manaoag with respect to transition period rainfall. Stations not in either class were considered intermediate. Areas which are similar during both transition periods are identified on Figure 3. The similar-different divisions determined by cluster analysis for the two transition periods are shown in Figure 4. Four clusters were formed for both transitions. In both cluster analyses, Matapitap did not conform to any grouping and therefore was ignored when boundaries were located. The area with a dry-wet transition similar to Manaoag's was much more extensive by cluster analysis than on the basis of b and R^2. However, the area with a wet-dry transition similar to Manaoag's was much less extensive, leading to a small area similar during both transitions. The major difference between boundaries located by the two methods was found for the dry-wet transition. Had the apparent data anomaly at Matapitap been recognized during the subjective classification, the boundary would have continued in a southeasterly direction, between Cabanatuan and Cabiao, instead of turning to the northeast. Both methods suggested that across the region, differences in dry-wet transition behavior were less significant than those in the wet-dry transition.

The simple method based on classification of b and R^2 from $Yij = bXij$ provided a useful insight into the weather pattern of the area. The clustering method, while apparently more correct because it included the effect of year differences embodied in the b_i, required computer facilities making the method impracticable for many cropping systems research projects. Regardless of method used, the rainfall series lengths are rather short, and as more years are added the boundaries should be relocated.

Return periods

Table 2 contains the Cabanatuan plotting points for the maximum 1- and 3-day rainfall totals for the dry-wet and wet-dry transitions. The corresponding plotting points for Dagupan are shown in Table 3.

Comparisons of maximum 1-, 2-, and 3-day rainfall totals showed little difference between point positions for low totals. The point positions of the high 2- and 3-day totals fell to the right of the 1-day totals, reflecting the accumulation of rainfall during tropical cyclones. The lower points tended to follow a straight line, while the higher points drifted to the right, suggesting that two distributions may be involved: one for frequent but relatively light transition period showers, and another for infrequent but relatively heavy tropical cyclone rains. The drift was more noticeable for the longer late dry-wet transition data, as illustrated by the contrast in Dagupan points for 1-16 May and 1 May-15 June (Fig. 5). Plotting the rainfall log for the 1 May-15 June data made the

Table 2. Return period plotting points for several Cabanatuan weather variables.

Return period (years)	Ranked maximum rainfall totals (mm) for 1- and 3-day, dry-wet transition						Ranked maximum rainfall totals (mm) for 1- and 3-day, wet-dry transition					
	1 May-16 May		1 May-31 May		1 May-15 Jun		15 Oct-30 Nov		1 Nov-30 Nov		1 Nov-15 Dec	
	1	3	1	3	1	3	1	3	1	3	1	3
1.03	0	0	9	9	19	22	4	4	0	0	0	0
1.07	0	0	10	13	23	32	8	8	8	8	8	8
1.11	0	0	15	19	23	40	8	10	8	10	12	14
1.15	0	0	17	21	35	42	12	13	10	13	13	18
1.20	1	1	19	22	40	48	15	23	12	14	14	23
1.25	2	2	21	26	43	52	22	33	13	23	15	23
1.30	2	2	22	30	44	61	28	39	14	23	20	24
1.37	2	3	25	43	49	66	30	48	15	24	22	26
1.43	10	13	26	47	49	68	31	51	20	26	22	30
1.50	16	17	31	52	50	71	33	53	22	30	23	33
1.58	16	17	35	54	53	81	40	60	23	33	28	45
1.67	17	17	41	57	53	81	50	70	28	45	28	48
1.76	17	18	43	61	56	83	50	77	31	48	31	51
1.88	17	19	46	62	58	84	51	79	33	51	33	62
2.00	19	24	49	62	62	85	52	80	40	58	40	65
2.14	19	24	50	67	63	94	56	81	50	70	50	70
2.31	22	36	51	70	71	110	61	86	50	79	51	79
2.50	32	41	53	71	71	120	65	90	51	80	52	80
2.73	32	44	56	74	74	125	76	96	52	81	61	81
3.00	35	47	58	77	80	125	79	104	61	84	62	84
3.33	39	57	61	83	81	126	85	107	62	90	76	104
3.78	41	61	62	85	81	132	86	107	76	104	79	107
4.29	43	71	62	92	82	137	93	149	79	107	85	107
5.00	43	77	74	95	87	149	94	161	85	107	93	145
6.00	53	80	80	120	100	160	98	161	93	149	94	149
7.50	62	85	87	126	185	210	122	169	94	161	98	161
10.00	80	95	100	132	197	334	124	183	98	161	122	161
15.00	87	120	197	334	226	583	145	196	122	169	139	169
30.00	100	126	226	583	526	600	231	306	145	183	145	183

Table 3. Return period plotting points for several Dagupan weather variables.

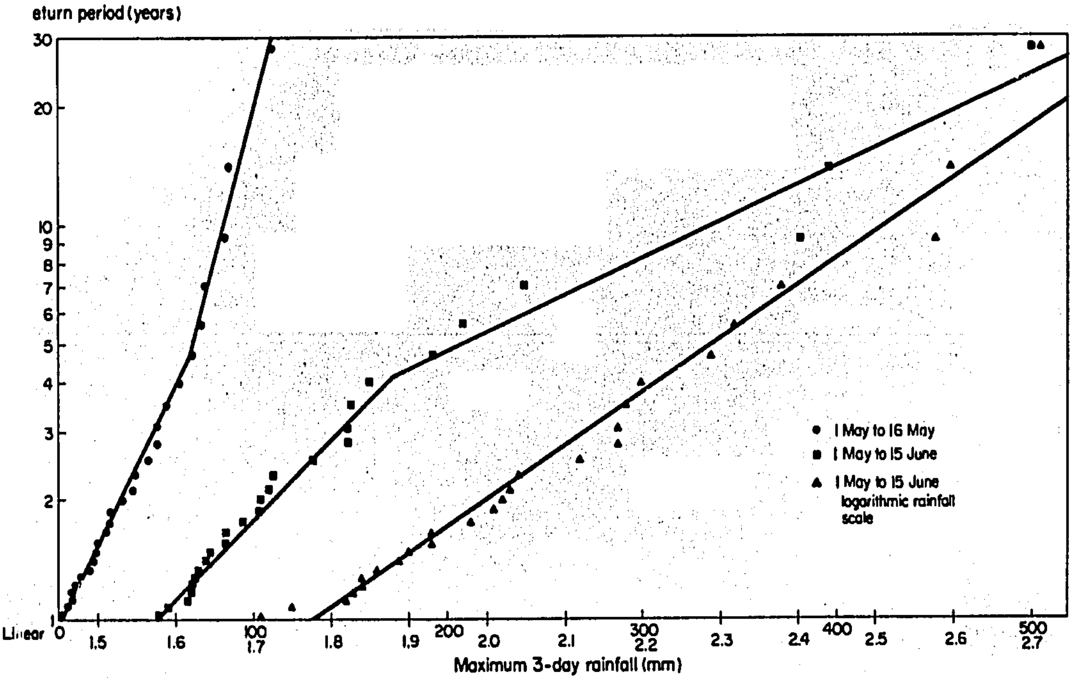
Return period (years)	Ranked maximum rainfall totals (mm) for 1- and 3-day, dry-wet transition: 1 May-16 May, 1	1 May-16 May, 3	1 May-31 May, 1	1 May-31 May, 3	1 May-15 Jun, 1	1 May-15 Jun, 3	Ranked maximum rainfall totals (mm) for 1- and 3-day, wet-dry transition: 15 Oct-30 Nov, 1	15 Oct-30 Nov, 3	1 Nov-30 Nov, 1	1 Nov-30 Nov, 3	1 Nov-15 Dec, 1	1 Nov-15 Dec, 3
1.04	2	3	5	7	29	51	10	10	3	3	5	5
1.08	4	5	16	37	36	56	13	17	5	5	8	8
1.12	5	7	28	35	38	66	16	21	8	8	8	14
1.17	6	7	29	39	39	68	17	22	8	14	11	14
1.22	7	9	33	39	40	69	18	26	11	16	13	16
1.27	11	11	33	43	49	70	18	28	13	17	14	17
1.33	12	16	36	45	50	72	25	29	14	18	14	18
1.40	13	18	37	45	51	76	28	30	15	18	15	18
1.47	16	19	38	48	55	79	28	33	15	18	15	18
1.55	20	20	39	51	56	86	30	34	17	19	17	19
1.65	23	25	40	55	56	86	31	38	17	22	17	22
1.75	24	26	41	56	57	95	31	40	18	23	18	23
1.87	26	27	43	66	64	.03	34	41	18	29	18	29
2.00	27	33	46	66	65	.04	34	43	25	32	25	32
2.15	27	39	47	69	65	108	34	43	30	33	30	33
2.33	29	40	49	70	70	110	34	43	30	34	30	34
2.55	34	46	50	72	71	131	35	53	31	38	31	38
2.80	39	51	56	76	74	149	38	53	31	41	34	41
3.11	40	51	56	86	84	149	43	53	34	43	38	43
3.50	40	56	58	87	93	151	46	64	38	53	39	53
4.00	41	63	65	93	121	160	49	68	39	62	46	62
4.67	46	69	65	108	128	193	52	69	46	64	50	64
5.60	50	74	70	110	144	208	64	93	50	68	52	68
7.00	55	76	71	149	170	239	68	98	52	69	58	69
9.33	56	86	74	151	188	382	82	159	64	69	64	86
14.00	71	89	188	208	196	397	142	176	68	98	68	98
28.00	74	110	332	502	332	502	153	223	142	176	142	176

relationship more nearly linear. Given the nature of rainfall patterns in the area, subsequent interpretations for cropping patterns in both the dry-wet and wet-dry transition were based on 3-day totals. Moreover, the differences between 1-, 2-, and 3-day totals were small at the lower end of the rankings, making the agronomic significance of a choice unimportant in the low range.

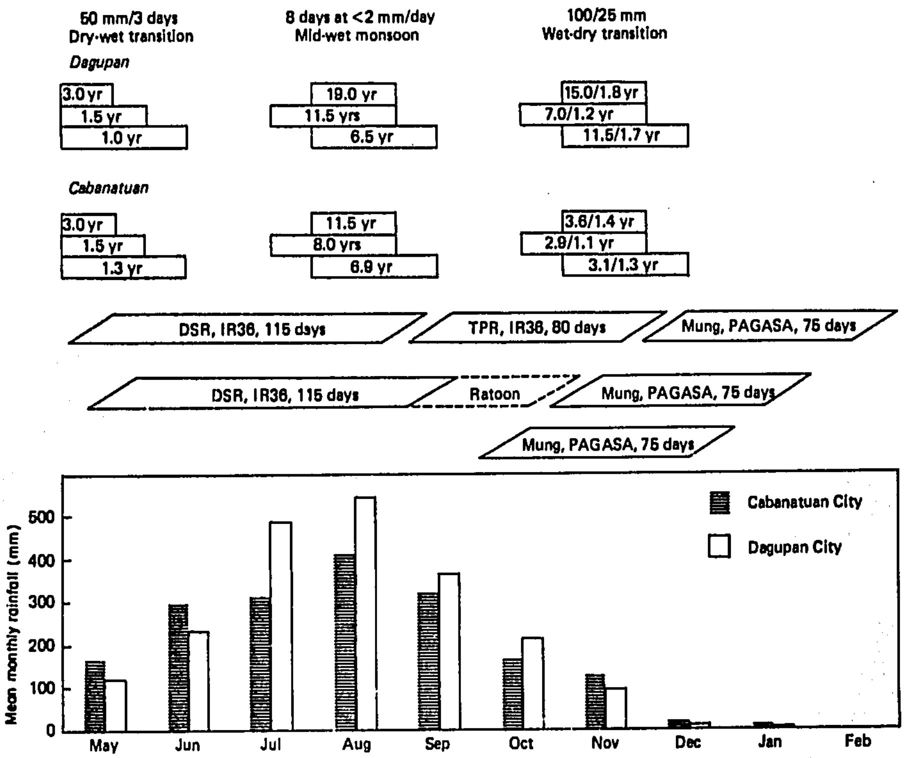
Return periods for selected totals during the transitions are shown in relation to the expected field durations of two cropping patterns (Fig. 6). No differences of agronomic importance for dry-seeded rice were found between Dagupan and Cabanatuan for the dry-wet transition period. The similarity in return periods derived from these longer series supports the results of the cluster analysis on the short-term series discussed earlier. The differences in return periods for the three intervals analyzed suggest that the first half of May will be unreliable near both stations, but later periods are likely to be more reliable.

For the three wet-dry transition intervals examined, Cabanatuan was more likely than Dagupan to have rain exceeding 25 mm/3 days, but the difference was not major, especially for the 15 October to 30 November interval. On the basis of 100 mm/3 days, Cabanatuan was clearly more frequently wet for all intervals compared. The dissimilar return periods for these two stations also support the results of the cluster analysis on the short-term series.

Assuming that return periods from Cabanatuan are representative, adjustments should be made in crop scheduling if patterns adapted to Manaoag conditions are attempted further south in the general vicinity of Tarlac-Cabanatuan City-Guimba-Paniqui. Dry-seeded rice scheduling does not need adjustment for the cropping patterns used to illustrate the analytical techniques, but planting schedules during the wet-dry transition should be significantly altered because mung bean planted shortly after dry-seeded rice harvest is likely to suffer from excess moisture if planting is



5. Return periods for maximum 3-day rainfall totals from 1 May to 16 May and from 1 May to 15 June. A logarithmic transformation was applied on 1 May to 15 June rainfall. Dagupan, Philippines.



6. Crop varieties and field durations, dry-wet and wet-dry monsoon transition rainfall criteria and return periods, mid-wet monsoon consecutive dry day criteria and return periods, and mean monthly rainfall for Dagupan and Cabanatuan, Philippines.

early. For the three crop patterns, the transplanted rice crop, which assumes that irrigation remains available through October and November, would apparently be slightly less irrigation dependent in the southern region.

CONCLUSIONS

The comparison between two methods of identifying areas with dry-wet and wet-dry monsoon transitions similar to Manaoag's, based on short-term rainfall records from 18 Central Luzon Valley stations, suggests that the simpler, subjective method may be adequate as a first approximation, but the more objective clustering method would be preferred. The short-term length of rainfall records limits either method. Under such circumstances, revised analyses should be made as additional records become available. In the region examined, dry-wet transitions similar to Manaoag's covered an extensive area, but the area with similar wet-dry transitions was more limited.

Return period analyses suggested that to avoid excess moisture damage, mung bean plantings may be delayed in the southern portion of the area, assuming the criteria are appropriate. Except for the western border, the period for dry-seeded rice planting should be approximately the same in the remainder of the area. For most of the area, expected dry-seeded rice planting would occur in late May.

The analytical techniques used to determine the locational similarities of transition periods are not difficult to apply. They can easily be used in field offices to make initial delineations of zones adjoining the research area which have similar monsoon transition patterns.

The return period analytical techniques are also easy to apply. It is important to realize that agronomic judgments are involved in the application of the techniques at three points: identification of the key intervals within the pattern to which the techniques should be applied, determination of the critical levels on which to base return periods, and interpretation of the probabilities. Knowledge of local crops, soils, and climatic factors governing potential evapotranspiration must be employed for the first two points. For the last, knowledge of agroeconomic factors, primarily the costs of alternative production methods and product prices, must be incorporated.

These techniques must be considered as interim aids for making subjective statements about extrapolation over years and locations. More objective methods but with simplicity retained should be developed.

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A weather-technology model for rice in Southern Brazil

F. S. da Mota and J. B. da Silva

An empirical-statistical rice yield-weather-technology model was developed for Pelotas County in the irrigated rice region of southern Brazil, with 15 years data on County yields, rice crop phenology, and monthly weather. The statistical multiple regression technique known as backward elimination was used in the selection of the best independent variable.

The model was tested for its predictive ability with data of years not included in the model. The absolute differences between observed and predicted yields range from 37 to 193 kg/ha for an average yield of 3,909 kg/ha.

Crop-weather models are becoming increasingly important for monitoring rice yield prospects in Brazil.

The present paper reports an example of an empirical-statistical yield-weather-technology model for the irrigated rice region in southern Brazil.

LITERATURE REVIEW

Crop-weather models are representations that simplify the complex relationship between climate and crop performance by using established mathematical or statistical techniques or both (Baier 1978).

Many papers report the influence of solar radiation on the yield of rice (Stansel 1969, 1975; De Datta et al 1968, Yoshida and Parao 1974). Low temperatures limit high rice yields (Moomaw and Vergara 1964, Sanchez 1971), as do high temperatures (Murata 1964). According to Matsushima (1957), each stage of grain development in rice requires a specific combination of night and day temperatures for maximum yield.

In a field experiment in southern Brazil, Andrade et al (1979) analyze a 4-year series of rice yields for 3 cultivars at 4 levels of nitrogen. They studied the influence of solar radiation, maximum and minimum temperatures at 30, 45, 60, and 75 days before harvest, and the number of days with minimum temperatures below 15°C in February. Yields of the semidwarf erect-leaf cultivar IAS-12-9-Formosa from Taiwan increased with an increase in solar radiation and average minimum temperatures 75 days before harvest. Yields decreased when the number of days with minimum temperatures below 15°C increased. The yields of the dwarf, erect-leaf cultivar Cica-4 from Colombia increased with an increase in solar radiation and maximum temperatures in the last 45-60 days before harvest. Temperature did not affect the yields of tall, droopy-leaf cultivar EEA-406 from Brazil.

MATERIALS AND METHODS

Empirical-statistical models use samples of yield and weather data from an area to estimate coefficients by some sort of regression technique (Baier 1978). Irrigated rice yields in Pelotas County (Rio Grande do Sul State, Brazil), for 1957 to 1972 were compared with weather and phenological variables and a technological index. The statistical multiple regression technique known as backward

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Table 1. Rice yields and meteorological, phenological, and technological variables. Pelotas County, Rio Grande do Sul State, Brazil, 1957-1972.

Harvest year	Rice yield (t/ha)	Area sown before 30 Nov (%)	Days with with min temp below 15°C in Feb	Av sunshine Feb and Mar (h)	Av max temp Nov to Jan (°C)	Av min temp Nov to Jan (°C)	Technological trend
1957	1.9	95	13	235	27.3	15.6	1
1958	2.7	21	6	229	25.3	18.3	2
1959	2.9	100	5	234	26.0	17.3	3
1960	2.7	55	4	211	26.3	16.7	4
1962	2.9	57	14	211	26.3	17.3	5
1963	3.1	95	3	220	26.7	16.7	6
1964	2.3	7	4	216	25.0	17.0	7
1965	2.6	10	8	213	26.3	15.3	8
1966	3.1	90	10	229	25.0	17.7	9
1967	3.4	84	6	198	25.3	17.0	10
1968	3.5	86	7	227	26.7	17.3	11
1969	3.3	100	6	247	26.3	18.0	12
1970	4.1	100	3	216	25.7	17.0	13
1971	3.1	100	4	229	25.7	16.0	14
1972	3.8	100	4	191	27.0	16.3	15

elimination (Draper and Smith 1966) was used to select the best variables for the estimation of Pelotas County rice yields.

To determine the equations, an IBM-1130 computer was used with a program developed by Silveira, Jr., and Zonta (1977). A 5% significance level was used to eliminate the nonsignificant variables.

The following independent variables were correlated to rice yields:

- x_1 = % of total area sown to rice until 30 November;
- x_2 = number of days with minimum temperature below 15°C in February;
- x_3 = average sunshine total in February and March;
- x_4 = average daily maximum temperatures in November, December, and January;
- x_5 = average daily minimum temperatures in November, December, and January; and
- x_6 = an index of technological change from 1957 to 1972 represented by an increasing order number (from 1 to 15).

The model tested was:

Yield (Y) = $a+b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_5x_5+b_6x_6$

Table 1 gives the values of the dependent and independent variables.

Table 2. Observed and predicted rice yields in Pelotas County, southern Brazil, 1973-76.

Harvest year	Yield (kg/ha)		
	Observed	Predicted	Difference
1973	3848	3970	122
1974	4122	4170	48
1975	3903	3710	-193
1976	3763	3800	37

RESULTS AND DISCUSSION

The following independent variables were significant:

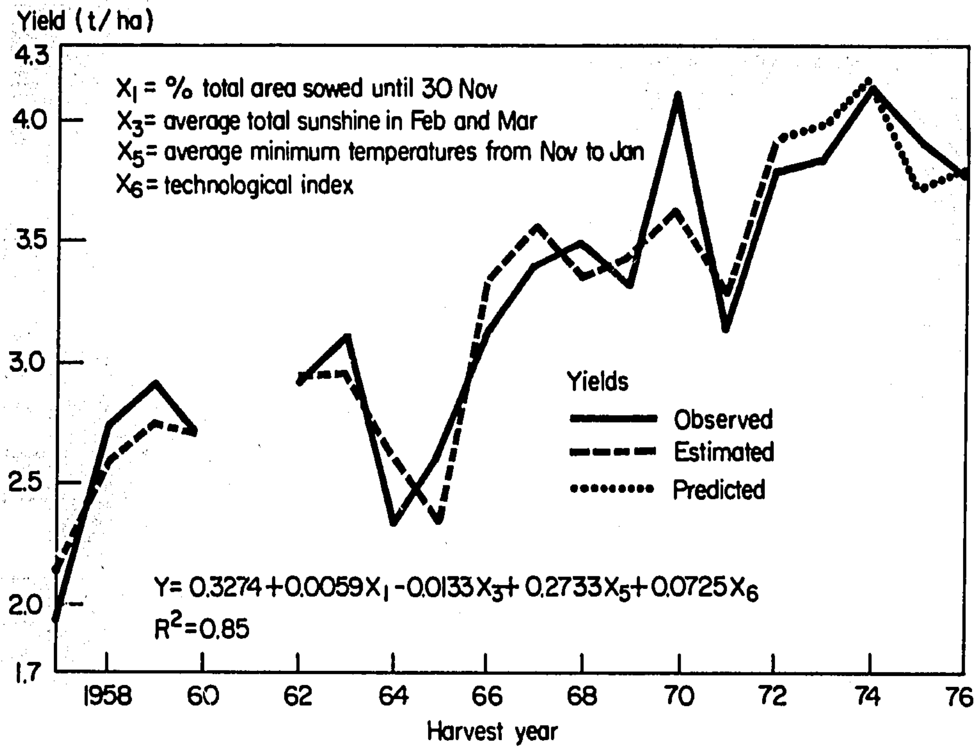
x_1, x_3, x_5, and x_6.

The following equation represents the yield-weather-technology model for irrigated rice in Pelotas County:

$$Y = 0.3274+0.0059x_1-0.0133x_3+0.2733x_5+0.0725x_6$$

This model was tested for its predictive ability with data of independent harvest years, 1973 to 1976. The results are shown in Table 2 and Figure 1.

Our results do not agree with those presented by Andrade et al (1979). For the cultivar EEA-406, which represents the type of cultivar used by Pelotas County rice farmers, Andrade et al report no influence of temperature and a slight response to solar radiation.



1. Observed, estimated, and predicted rice yields in Pelotas County, Brazil, 1957–76.

The negative response of Pelotas County rice yields to solar radiation could be explained as an indirect effect due to high pond evaporation decreasing the water available for irrigation. Many farmers in the region grow more rice than is advisable considering the water available for irrigation.

The response of Pelotas County rice yields to minimum temperatures may be linked to delays in sowing, a fact not present in the Andrade et al field experiment.

It seems likely that a model developed from field experiments may not agree with a more general model developed in the same region using actual yield data obtained from farmers.

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An analogue approach for estimating rice yield in China

A. Y. M. Yao and S. K. LeDuc

Analogue rice yield models were developed for the Lower Yangtze and Chujiang regions, both important for rice production in China. Based on a long series of reliable climatic and yield data, Kyushu (Japan) and northern Taiwan were selected as the analogous rice regions for the Lower Yangtze and Chujiang, respectively. The regression models have the general form:

$$\hat{Y}_i = \hat{\beta}_0 + \sum_{i=1}^{n} \hat{\beta}_i X_i$$

where: $\hat{Y}_i$ is the predicted yield; $\hat{\beta}_0$ is the estimated regression constant, and $\hat{\beta}_i$ is the ith least squares estimate of regression coefficients for the ith predictor, X_i.

Indices of predicted rice yields are discussed.

This report presents a method of estimating rice yields when either yield or climatic records are not available. In the absence of such data, an analogue model can estimate relative yield for the country under study using meteorological data from a country with similar climatic and agronomic conditions. Recognizing the limitations imposed upon the analogue technique (i.e. no quantitative yield data, the requirement of similarity of conditions), this approach may be used to assess crop conditions and provide qualitative estimates of potential rice yield fluctuations based on meteorological information.

The analogue model method includes three parts: 1) find analogous areas that have climatic and agronomic data available, 2) develop rice yield models using the regression technique, 3) develop relative yield indices to assess the fluctuation of rice yield. The goal is to provide a qualitative assessment of rice yield when quantitative estimate is not possible.

This procedure was developed for the Chujiang Region (including Kwangtung, the southern part of Fukien, and Jiangsi, and the southeastern part of Kwangsi) and the Lower Yangtze Region (including central Anhuei and most of Jiangsu, except the area north of the Huai River) with models developed in Kyushu (Japan) and northern Taiwan. China is one of the most important rice-producing countries in the world. Chujiang and the Lower Yangtze Regions are important rice-producing areas in China.

CLIMATIC AND YIELD DATA

Kyushu

Climatic data from the seven Kyushu stations are from the 1901 to 1973 annual reports of the Japanese Meteorological Agency, Tokyo. Rice yield data for the seven Kyushu prefectures are from the Japanese Agricultural Yearbook, Ministry of Agriculture and Forestry, Tokyo. Rice yields in 1945 had been affected by the war and were omitted. Yields for 1949, 1964, and 1970 were adjusted for losses due to typhoons.

Northern Taiwan

The climatic data from 1924 to 1952 for Taipei, Hsinchu, I-lan, and

Center for Environmental Assessment Services, Environmental Data and Information Service, National Oceanic and Atmospheric Administration, Washington, DC 20235, USA.

Taoyuan are from the Summary of Meteorological Data in Taiwan, Taiwan Provincial Weather Bureau, Taipei. Data from 1953 to 1974 were supplied by the Taiwan Provincial Weather Bureau. Rice yield data for the four northern counties are from the Taiwan Agricultural Yearbook, Department of Agriculture and Forestry. Rice yields in 1945 and 1946, were omitted. Yields in 1956, 1963, 1970, 1971, 1972, and 1973 were adjusted for losses due to typhoons during the second rice crop.

Chujiang and the Lower Yangtze Regions

Climatic data for stations in Canton, Amoy, Swatow, Wuchow, and Nanling in Chujiang Region; and Shanghai, Tungtai, Chengjiang, Wuhu, and Nanking in the Lower Yangtze Region are from the Climatological Data of Precipitation and Temperature (two volumes) in China, published by the Central Meteorological Bureau of Peking in 1954.

PHENOLOGICAL INFORMATION

Kyushu

Rice is usually planted in Kyushu in mid-May, transplanted in late June, heads in early September, and is harvested in late October (Crops Statistics No. 17, 1975, Ministry of Agriculture, Tokyo, Japan). Panicle formation is usually about 24 days before heading. Kyushu generally harvests one rice crop each year.

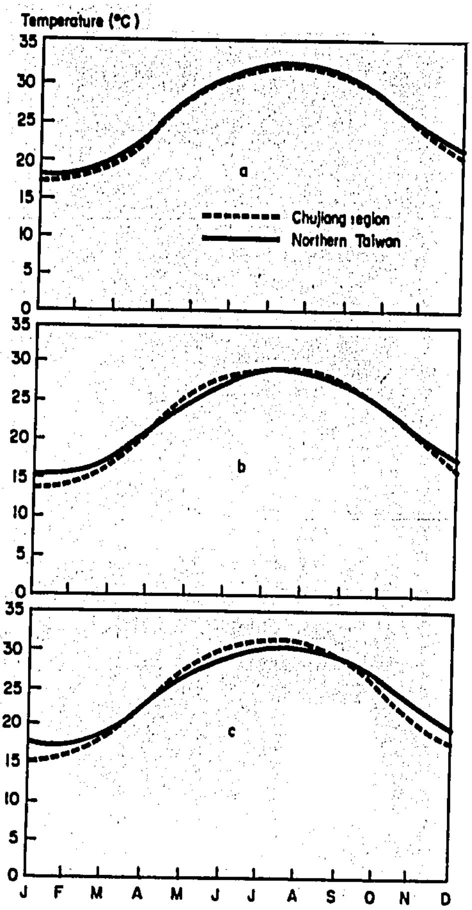
Northern Taiwan

In northern Taiwan two rice crops are usually harvested. The first is usually planted in late February and harvested in mid-July. The second is planted in mid-July and harvested in mid-November (Report on Agricultural Basic Survey in Taiwan, Department of Agriculture and Forestry, Taiwan Provincial Government, 1961).

ANALOGOUS AREAS

Climate of Chujiang Region and Northern Taiwan

The climates of Chujiang Region and northern Taiwan are both subtropical and tropical. The mean monthly temperatures and mean monthly maximum temperatures of the two regions match very well (Fig.1a,b). The mean monthly minimum temperatures are slightly different (Fig.1c), but the differences are not important. All the



1. a) Mean monthly maximum, b) mean monthly, and c) mean monthly minimum temperature for Chujiang Region and northern Taiwan.

mean monthly minimum temperatures are above 10°C, and the mean maxima are below 40°C, which are suitable temperatures for rice cultivation, especially in the double-rice cropping region. Other climatic factors, such as accumulated degree days with a base temperature of 10°C (4,318 in Chujiang and 4,376 in northern Taiwan), the frost-free days (348 in Chujiang and 358 in northern Taiwan), and the percentage of total possible sunshine (44 in Chujiang and 40 in northern Taiwan), are also very close for the two areas. There is ample rainfall in both regions (Table 1); however, moisture supply from month to month during the year still varies. The monthly distribution of precipitation in both regions shows a summer concentration. The ratio of ET (actual evapotranspiration) to PE (potential evapotranspiration) in both regions is high. Typhoons threaten with roughly the same frequency here as they do in Taiwan and southeastern coastal China.

Table 1. Mean monthly total precipitation and mean monthly ET:PE[a] of northern Taiwan and Chujiang Region.

	Northern Taiwan		Chujiang Region	
	Precipitation (mm)	ET:PE	Precipitation (mm)	ET:PE
Jan	99	1.00	37	1.00
Feb	133	1.00	64	1.00
Mar	160	1.00	92	1.00
Apr	194	1.00	138	1.00
May	220	1.00	202	1.00
Jun	315	1.00	225	1.00
Jul	167	0.99	199	0.99
Aug	241	1.00	210	1.00
Sep	198	1.00	119	0.98
Oct	120	0.94	63	0.89
Nov	84	0.90	43	0.86
Dec	84	1.00	38	1.00

[a]ET = actual evapotranspiration, PE = potential evapotranspiration.

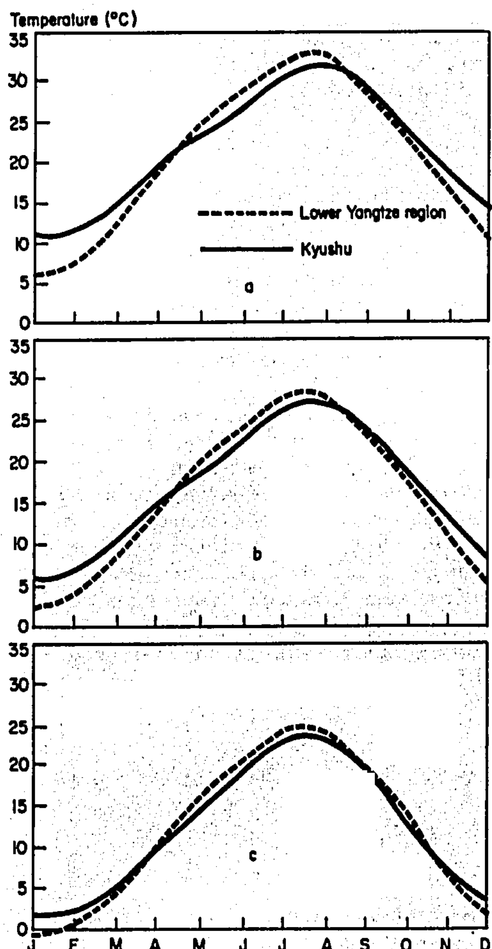
Climate of the lower Yangtze Region and Kyushu

The climate of the lower Yangtze Region and Kyushu are within the temperate zone and is, to some extent, regulated by the ocean. The four seasons are about evenly divided. The agricultural climate in both regions may be considered comparable in spite of some climatic differences.

Figure 2 illustrates the comparative temperatures in the two regions. The mean maximum, mean minimum, and mean temperatures are 2° to 3°C higher in Kyushu than in the lower Yangtze Region during the winter months, but are about the same in March and April. After April the situation is reversed for a few months. Temperature differences between the two regions are negligible from July on.

Inoue et al (1965) reported that the critical daytime mean temperature for transplanting rice in Japan is 15°C. Van Royen (1954) suggested a minimum of 10° to 12°C for germinating nontropical varieties. Figure 2c shows that all the minimum temperatures in both regions during the seeding and transplanting period are above these limits. Both regions have the temperatures required for most of the summer crops throughout their growing period. For example, rice during its growing period can tolerate temperatures as high as 37° to 40°C, and these are rarely exceeded in either region.

The accumulated growing degree days (2,514 in Kyushu and 2,578 in the



2. a) Monthly mean maximum, b) mean monthly, and c) monthly mean minimum temperature for the Lower Yangtze Region and Kyushu.

Lower Yangtze) are similar. The frost-free days are also comparable (238 in Kyushu and 242 in the Lower Yangtze Region). The mean annual percentage of possible sunshine is 52% on Kyushu and 47% in the Lower Yangtze.

The mean monthly precipitation of Kyushu is considerably higher than that of the Lower Yangtze. However, the calculated ratios of ET-PE in both regions are not significantly different. There are only a few months in the lower Yangtze Region where the monthly ratio of ET-PE is lower than unity, while on Kyushu there is no month with a ratio lower than one.

Agriculture and soils of all regions

Because of the climatic similarity, agriculture in the Chujiang and the Lower Yangtze Regions are comparable to that in their analogous areas. The major crops, land utilization, cultural methods, and crop rotation are also the same, but yields, varieties, and the utilization of chemical fertilizer differ.

Rice is the most important crop in the study areas and their analogues. The pattern and distribution of paddy fields are similar: the best land is usually planted to rice. The cultural methods and crop rotations are about the same; rice is usually sowed and harvested with small machinery. Planting and harvesting times are also comparable.

Detailed soil information for Chujiang and the Lower Yangtze Region is not available. The most important soil, covering extensive areas in all the four regions, is alluvial soil, which is predominantly planted to rice. Even though alluvial soils vary greatly in chemical and physical properties, they are similar in texture -- usually light or medium -- and in natural drainage -- usually poor.

MODELING

The linear regression technique is used in this study. The models have the general form:

$$\hat{Y}_i = \hat{\beta}_0 + \sum_{i=1}^{n} \hat{\beta}_i X_i \qquad (1)$$

where $\hat{Y}_i$ is the predicted yield; $\hat{\beta}_0$ is the estimated regression constant, and $\hat{\beta}_i$ is the ith least squares estimate of regression coefficients for the ith predictor, X_i.

In addition to meteorological variability related to crop yield, technological changes such as fertilizer application, the improved genetic quality of seeds, and random noise (McQuigg 1975) due to the random events not specifically included in the model must be considered. A stepwise regression technique (Draper and Smith 1966) is used to construct all the models. All the variables in the stepwise regression are significant at the $\alpha = 0.10$ level.

Northern Taiwan models

Regression models were constructed separately for each of the four counties for the period 1950-1975 for two rice crops. Both northern Taiwan and Chujiang Region are double rice crop regions. Variables include mean temperature, total monthly precipitation, and mean percentage of total possible sunshine for the month. Cropping months are February through July for the first rice crop model, and July through November for the second. Results showed that for the first rice crop the models are sensitive to these weather variables (Fig.3,4 and Table 2). The multiple correlation coefficient (R^2) ranged from 0.98-0.94. The predictibility of the second rice crop model is rather low (Table 3). The inability to determine a good and meaningful model may be partially explained by the fact that the very high yield fluctuation of the second crop is caused by meteorological variables and also by factors that are not presently considered, such as pests. The model for the second crop for Taoyuan is, however, somewhat better than the others (Table 3).

In addition to the individual models, an overall combined model was developed for both crops. Equation 2 is for the first crop and equation 3 is for the second crop.

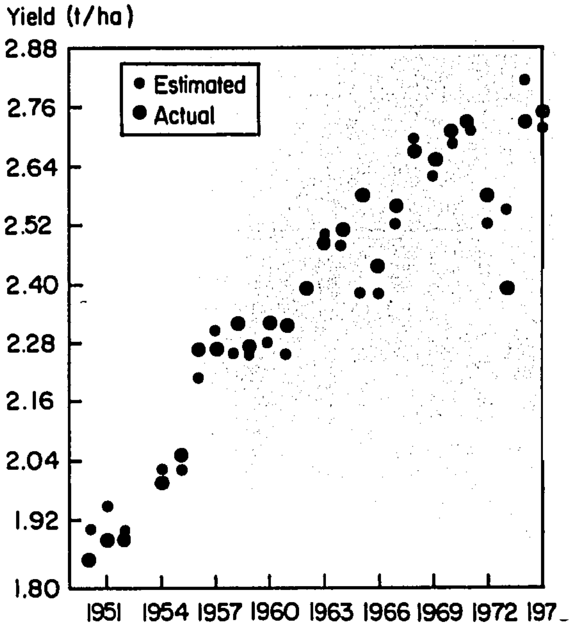
$$\hat{Y}_i = 951.82+60.39T+90.90REG-4.02TM2+4.79TM6 \qquad (2)$$

$$\hat{Y}_i = 119.78+48.08T-198.95REG+5.81TM10 \qquad (3)$$

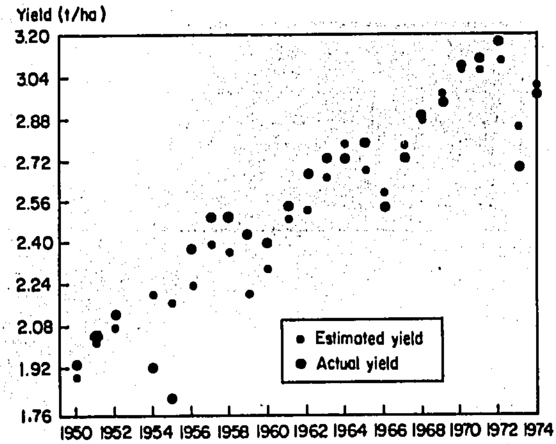
where $\hat{Y}_i$ is the estimated yield (t/ha), T is the technological trend, TM is the mean monthly temperature (0°C), numbers 2 to 10 mean February through October, and REG is a dummy variable which is 1 if the estimate is for Hsinchu-Taoyuan, 0 otherwise.

Kyushu models

Regression models were constructed for each of the seven prefectures separately



3. Observed and predicted first crop for Taipei, using the multiple regression model.



4. Observed and predicted first rice crop for Hsinchu, using the multiple regression model.

for 1901-1973 (1945 omitted) and 1947-1973 using monthly mean, mean maximum, and mean minimum temperatures; mean monthly precipitation; total cumulative precipitation from June to September; and mean monthly percentage of total possible sunshine for May through October. Figure 5 shows that the estimated yields were quite close to actual yields. In some cases, however, the estimated yields deviated considerably. R^2 for the models ranged from 0.86-0.94 (Table 4). Figure 5 also showed no apparent yield increase because of technological considerations for 1901-1944, but a steeply rising trend occurred thereafter. Figure 6 shows that the shorter period models give better results. Table 4 includes the estimated coefficients, the R^2, and the residual standard deviation (S_e) for all seven models.

In addition to the seven models, an overall model which estimates the yield for all of Kyushu was constructed using data from 1947 on.

$$\hat{Y}_i = 237.93+6.07T-0.24TN10-0.01P_{j-8}+0.04TS9+100.06D2+72.14D3+38.34D4+60.71D6 \quad (4)$$

Table 2. Mean monthly total precipitation and mean monthly ET:PE[a] of northern Taiwan and Yangtze Region.

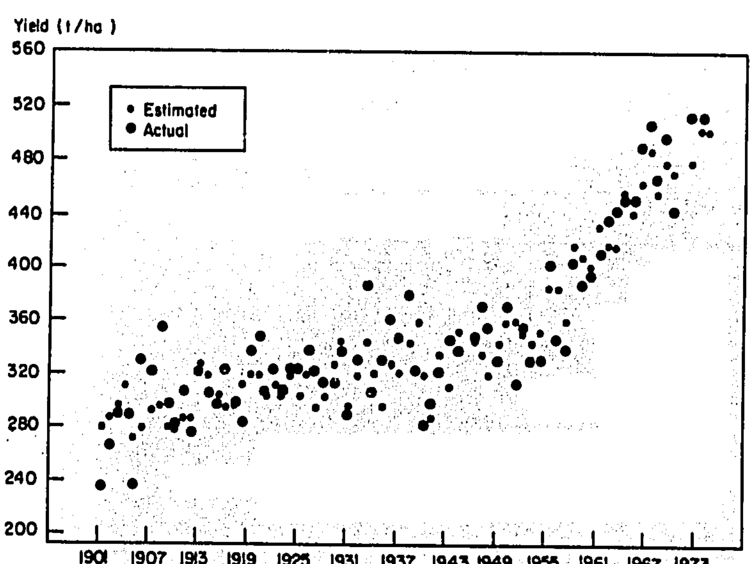
	Kyushu		Yangtze Region	
	Precipitation (mm)	ET:PE	Precipitation (mm)	ET:PE
Jan	68	1.00	46	1.00
Feb	88	1.00	56	1.00
Mar	138	1.00	79	1.00
Apr	188	1.00	97	1.00
May	147	1.00	95	1.00
Jun	295	1.00	175	1.00
Jul	295	1.00	164	0.99
Aug	193	1.00	143	0.97
Sep	231	1.00	115	0.97
Oct	139	1.00	58	0.97
Nov	92	1.00	51	1.00
Dec	77	1.00	44	1.00

[a]ET = actual evapotranspiration, PE = potential evapotranspiration.

Table 3. Weather-rice yield models for northern Taiwan, 1950–75.

Variable[a]	Taipei		Hsinchu		I-lan		Taoyuan	
Intercept	1973.24	1467.99	2614.59	1710.93	2674.17	1683.60	1383.43	1136.11
Trend	34.72	12.32	47.35	40.99	64.34	27.76	64.84	49.61
TM2					-5.10			
TM3			-3.38					
TM4	-4.09							
TM5								
TM6								
TY'								
Th								
Th								
Th								
TF					-0.10			
TF								
TP			-0.07					
TP					-0.05			
TP								
TP7		0.03				0.06		
TP8		0.03						
TP9								
TP10								
DR2							-0.15	
DR3								
DR4	0.30							
DR5	0.11						.17	
DR6								
DR7	0.13							
DR8								
DR9								
DR10								0.27
R^2	0.94	0.46	0.89	0.65	0.97	0.46	0.93	0.82
SD	76.78	129.43	137.77	225.96	105.55	240.38	140.13	180.18

[a]TM = mean monthly temperature (0°C), TP = monthly total precipitation (mm), DR = duration of sunshine (hours), numbers 2 to 10 = February to October.



5. Observed and predicted rice yields for Fukuoka, using the multiple regression model (1901–1973).

Table 4. Weather-rice yield models for Kyushu, 1947-73.

Variable[a]	Fukuoka	Kumamoto	Miyazaka	Saga	Oita	Nagasaki	Kagoshima
Intercept	395.31	-7.10	131.51	452.87	310.38	399.19	-105.48
Trend	7.37	5.47	6.00	8.27	6.46	5.76	4.62
RG5							
RG6						-1.11	
RG7	1.58						
RG8							
RG9							
RG10							
TM5							
TM6							
TM7							
TM8					-1.55		-1.20
TM9		1.04			1.09		
TM10							0.40
TN5							
TN6							
TN7		1.84					
TN8						-0.79	
TN9							
TN10							
TX5X							
TX6							
TX7							1.99
TX8							
TX9			0.50				
TX10				-1.34			
TS5							
TS6		.02					
TS7						0.02	-0.02
TS8				0.03	0.06		
TS9	0.05	0.03		0.06		0.04	
TS10							
TP							
P_{j-s}			-0.01				
R^2	0.93	0.86	0.89	0.87	0.94	0.91	0.92
SD	18.98	26.86	19.00	28.57	12.11	14.52	13.95

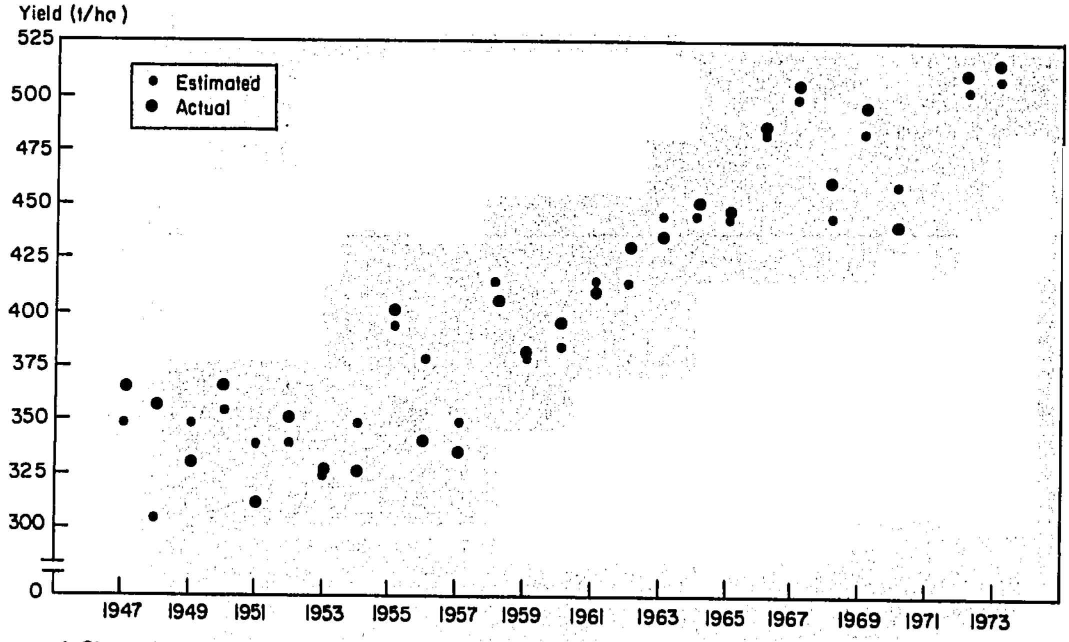
[a]RG = temperature range (0°C) mean maximum - mean minimum
TM = mean monthly temperature (0°C)
TX = mean monthly maximum temperature (0°C)
TN = mean monthly minimum temperature (0°C)
TS = mean monthly % sunshine
TP = total monthly precipitation (mm)
P_{j-s} = cumulative precipitation, June to September (mm)
5 = May, 6 = June, 7 = July, 8 = August, 9 = September, and 10 = October

where $\hat{Y}_i$ is the estimated yield (t/ha), T is the technological trend; *TN*10 is mean minimum temperature (0°C) in October; P_{j-s} is the total precipitation (mm) from June through September; *TS*9 is percentage of total possible sunshine in September; *D*2 is 1 if the estimate is for Saga, 0 otherwise; *D*4 is 1 if the estimate is for Oita, 0 otherwise; and *D*6 is 1 if the estimate is for Kumamoto, 0 otherwise.

YIELD INDEX

Direction and magnitude of yield

Models developed with data from Kyushu and northern Taiwan were applied to meteorological data from Chujiang and the Lower Yangtze Region for 1924-1942. The simulated yields were compared with actual yields in Kyushu and northern Taiwan. These data are completely independent of



6. Observed and predicted rice yields for Fukuoka, using the multiple regression model (1947–1973).

the data from later years used in developing the models. The simulated yields were standardized by subtracting the mean of the simulated yields, then dividing by the standard deviation. This was also done to the actual yields. Standardizing each series was necessary to compare the direction and magnitude of the fluctuation. The simulated yields for 1924-1942, derived from models developed from a more recent period, have a mean different from that of the actual yield for that period. Thus, subtracting the mean adjusts for this. The simulated yields also can show larger deviations so that dividing by the standard deviation is necessary to compare the two series. The results of the study show that, in general, the actual and the simulated yiels vary in the same direction.

Rice yield data for 1931-1937 in the Lower Yangtze Region were compared with those for Kyushu for the same period. The yield level was not the same, but the direction of variation was similar. Rice yields from 1931-1945 for Chujiang Region were also compared with those of northern Taiwan. The yield fluctuation in the two areas did not agree, partly because these data include both first and second crops. However, level trends in both areas were indicated.

Information gained from these comparisons supports the use of the analogue approach for estimating rice yield in China.

Indexing

In areas where actual yield data are not available but an appropriate analogue model is available, an index which indicates yield fluctuations due to weather can be provided. There are several methods of calculating such an index using simulated yields from the analogue model. One method is to compare the simulated yield for a particular year to the simulated yield using the average values for the weather variables. The index could be a percentage of the yield simulated with average weather or a percentage deviation from this yield.

A second method consists of several steps. First, the long-term average weather in the analogous region is used to derive a simulated yield. Second, the simulated yield is compared with the historical mean yield and a ratio is formed. Third, the long-term average weather is used to derive a simulated yield in the area under study. It is then assumed that the ratio of historical yield to simulated yield in the area under study is the same as that in the analogous region. The long-term mean yield in the study area is then readily derived. The ratio of the simulated yield to the historical yield is an index of the percentage of normal yield. It is assumed that the ratios are similar if both regions have similar trends and the yield variations are in the same direction. If weather data are available for a series of years, the third alternative is to compute the simulated yield for each of those years, then derive the percentiles of the series. The simulated yield index for each year could be expressed as the percentile rank. Perhaps the best policy is to provide a range of values falling within a particular group.

CONCLUSION

Weather data from 1924 to 1942 are available for Chujiang and the Lower Yangtze Region. Six hourly synoptic weather reports, which include the meteorological variables needed for the simulation yield models for the two regions, are also available. With this meteorological information and the analogue yield models developed regions, qualitative assessments of rice yields in Chujiang and the Lower Yangtze can be compared.

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Report of working groups

Background information

The first Planning Meeting was held on the afternoon of Wednesday, 5 December 1979 with Dr. Baier as chairman. The meeting decided to establish three working groups with the following tasks:

Working Group I
To determine the status of National Weather Records in rice-growing regions and to plan how these may be collected, analyzed and made available to national and international organizations currently in need of these data.

Working Group II
To determine the minimum essential meteorological variables which should be monitored in rice-weather experiments including planning of experiments along the lines established in previous symposia on wheat and maize.

Working Group III
To develop plans and priorities for rice-weather data analysis, i.e. synthesis and modeling activities, to be accomplished assuming the data involved in I and II above become available.

The chairmen and rapporteurs of the working groups were:

Working Group I
Chairman: Dr. L. R. Oldeman
Rapporteur: Mr. Chan Ah Kee

Working Group II
Chairman: Dr. Z. Uchijima
Rapporteur: Dr. J. F. Angus

Working Group III
Chairman: Dr. J. W. Stansel
Rapporteur: Dr. R. E. Fries

The Planning Meeting also approved the following guidance material to be provided to the working group chairmen:

Guidance material for working group chairmen

a) Agricultural technology is highly weather-dependent and may become more vulnerable to climatic variability - because of higher input except for areas where water is controlled.

b) Rice is grown under more diverse environmental conditions than any other food crop in the world. But research on rice-weather relationships is far behind compared to our knowledge of the agrometeorology of other cereal crops (e.g. wheat or maize).

c) Rice is the leading crop in parts of the world where:
- population densities are highest
- population growth is well above the 2% per year world average

d) Rice is the major diet of 1.5 billion people, i.e. 40% of world population. Every year an additional 43 million people will depend on rice as major staple food. An annual increase of 8.6 million tons of rough rice is needed. To meet this demand for food, weather and climate must be more fully considered in production planning, increased yield and improved quality.

e) Major rice producing areas are also major rice consuming areas. World carry-over is small, about 3% of world production. A weather-induced large-scale drop in production could result in an immediate shortage of rice supply with disastrous consequences and hence there is an urgent need to monitor rice production.

f) There is a need for testing research results under various climatic conditions; involvement of farmers must be considered in all these aspects.

g) There exist widespread problems in obtaining good climatic data and in receiving near real-time meteorological data from the national meteorological services.

h) World Climate Programme and National Climate Programmes provide the framework for interagency cooperation in climatic variability studies.

i) There is a growing awareness of the potential impact of climatic variability on human activities and also of the possible effects of human activities on climate. Agriculture must provide evidence for these assumptions.

j) The first step is to document requirements by agriculture for climatological information.

Objectives

a) To review progress since the 1974 IRRI Climate and Rice Symposium.

b) To identify problem areas:
- lack of knowledge
- lack of data
- lack of communication

c) To document data sources and data availability.

d) To develop a plan of action for rice-weather experiments which provide a good data set suitable for analysis and modeling.

e) To formulate conclusion and to make proposals for the participation and further action by international and national agencies, in order to meet the requirements of both developed and developing countries.

Proposals

These should be directed to:

a) permanent representatives of countries with WMO

b) Secretary-General of WMO

c) agricultural ministries (to be arranged by FAO; WMO to initiate the primary action).

Working Group I: Climatic data

a) Climatic data requirements (general)

b) Climatic data sources

c) Availability of climatic data
- national weather services
- regional centers
- world meteorological centers

d) Exchange of data
- historical
- near real-time (WWW system)
- proposals for improvements in climatological data exchange

e) Station location and density

f) Spatial interpolation (grid points)

Working Group II: Minimum data requirements

a) Observed agrometeorological data

b) Derived agrometeorological data

c) Data required in rice-weather studies depending on scale
- micro-scale (field plots)
- meso-scale (farmer's fields)
- macro-scale (regions)

Data required in rice-weather studies depending on type of rice cultivation
- rainfed upland
- rainfed and inadequately irrigated
- adequately irrigated

d) Other environmental data (e.g. soil, topography)

e) Biological data (crop development and crop yields)

f) Proposals for acquisition of rice-weather data

Working Group III: Data analysis and modeling

a) Emphasis on *use* of data for
- interpretation of field experiments
- Crop-weather models
- Classification
- Other uses

b) Time scale
- Averages or normals
- Annual
- Monthly
- Weekly
- Daily
- Hourly
- Interpolation overtime

c) Space
- Density of stations
- Interpolation over space

d) Climatological or archived data vs near real-time weather data.

Identification of data requirements in view of data uses

Proposals for development of methodology for data analysis and modeling.

Recommendations of Working Group I - Climatic data

Determination of the status of national weather records

At present the ASEAN Sub-committee on Climatology is compiling climatic information from Indonesia, Malaysia, Philippines, Singapore and Thailand for the preparation of a climatic atlas and a compendium of climatic statistics according to agreed-upon formats and methods with quality control checking. The climatic data are put on magnetic tape and summarized climatic data for large number of locations will be published at the end of 1980.

The national meteorological services maintain a network of weather stations. Location, type of station, and its status are inventoried and reported to WMO. Weather data are recorded and processed by the national meteorological services.

The working group on climatic data does not consider it its duty to review the status of the climatic data acquisition of the national meteorological services, since this would require intensive consultation with their respective meteorological services.

Weather data are collected by many agencies and bodies for their own needs, sometimes without any consultation with the national meteorological services. It is, therefore, sometimes impossible to get a good impression of the total network density of the stations operating in the country, while another drawback is that climatic variables are not recorded uniformly, equipment varies from place to place, and quality control is not assured.

Recommendations

1. It is recommended that raw weather data collected by the national meteorological services should, after quality check, be put on magnetic tape for the convenience of users of these data. It is hoped that WMO can render assistance in this regard to the developing nations.
2. It is recommended that various agencies - national or international - recording climatic variables work out their activities in close cooperation with the national meteorological services.

Climatic data requirements

It appears that there is a need for climatic data with regard to monitoring rice-weather experiments and in relation to crop-weather models, classification and agroclimate mapping. Three sets of climatic data are required.

Historic climatic data. For classification purposes, but also for the development of crop-weather models, there is a need for long-term climatic records. These data could be obtained from various sources but primarily from the national meteorological services.

Current and future climatic data for rice-weather experiments. If it is decided to set up rice-weather experiments, e.g. according to the multiple cropping outreach programs, climatic data should be recorded if possible on the spot or in close vicinity of the experimental site. These climatic stations could be operated and maintained by a special body in charge of the rice-weather experiments in close cooperation with national meteorological services or by the meteorological services themselves.

Recommendations

3) It is recommended that results of ongoing agricultural research experiments - agronomic trials, variety trials, etc. - be accompanied, where possible, by relevant climatic data.

4) It is recommended that any interchange of near real-time climatic data should take advantage of the WMO CLIMAT message format and procedures.

5) It is recommended that at outreach sites where rice-weather experiments are conducted, equipment for climatic data collection is simple and easy to maintain.

Current and future climatic data to monitor crop yields on a regional scale. This could require the upgrading and/or installation of climatic stations in areas relevant to this monitoring. These stations should become part of the national agrometeorological network.

Recommendation

6) It is recommended that the appropriate national agencies be given the responsibility of carrying out the rice yield and climate monitoring in cooperation with the respective national meteorological services.

Interaction between national meteorological services and agricultural agencies. The links between national meteorological services and agricultural agencies appear to be weak. Even within national agricultural research bodies and their own supporting meteorological services interaction is not well developed.

Recommendation

7) It is recommended that the national meteorological services should at least every 2 years obtain a feedback from the consumer research agencies (e.g. hydrometeorological services, agricultural agencies) by means of questionnaires, meetings, etc. with regard to the adequacy of network density, instrumentation, and exchange of data and other services provided by them. This would provide an opportunity to the national meteorological services and other agencies to review available facilities in the light of research priorities.

Recommendations of Working Group II Minimum data requirements in rice-weather experiments

1) The working group recommends to WMO that a co-ordinated series of rice-weather experiments be conducted along the lines of previous WMO international experiments on wheat and lucerne and appropriately modified for the particular problems of rice. Priority should be given to the wetland and dryland rainfed cultural types.

2) For this purpose WMO should set up a working group of participating researchers and in collaboration with IRRI and relevant national and international organizations. The terms of reference of the working group should include the formulation of plans for a co-ordinated series of rice-weather experiments. The group should consider the appropriate design and implementation of the experiments and the analysis of the data obtained. The group should be convened under the joint leadership of WMO and IRRI and work in consultation with appropriate national and international organizations. In the collaborative experiments, a standardized set of weather, edaphic, and biological data should be collected. Weather data recommended are given in Table 1. Edaphic and biological data are to be decided upon by the working group with reference to previous recommendations on this topic. The existing multi-location testing of rice varieties and lines should be reinforced with weather and edaphic data.

3) WMO should encourage national and international organizations to analyze existing rice/weather data already available.

4) Basic research on micrometeorological processes in tropical rice should be encouraged in adequately equipped groups. Recommendations for data to be collected are in Table 2.

Recommendations of Working Group III - Data analysis and modeling

1) Recommend that WMO cooperate with national meteorological services and other appropriate groups in the assessment of the optimum distribution of climatological stations required to provide data for meaningful agroclimatic analysis.

2) Recommend that the following measurements be taken by "Ordinary Climatological Stations" on a density of 1 per 1000 km^2 (or as modified by recommendations in I above) on a daily basis for near real-time use.

a. Temperature
   1) Maximum
   2) Minimum
b. Precipitation (total)
c. Solar radiation
   1) Net radiation
   2) PAR radiation
d. Evaporation

Table 1. Minimum agrometeorological data recommended for a series of collaborative rainfed rice-weather experiments.

	Wetland	Dryland	Note
Air temp (max., min.)	x	x	Daily
Soil temp (max., min.)	x	x	Depth 5 cm
Relative humidity (max., min.)	x	x	Daily
Rainfall	x	x	Daily
Global radiation and/or sunshine duration	x	x	Daily
Pan evaporation	x	x	Daily
Water temp (max., min.)	x	x	Daily
Volumetric soil water content		x	Twice during the crop cycle, e.g. planting and flowering
Water depth	x		Daily or weekly
Volumetric soil water retention at saturation, upper and lower limits of available water	x	x	Once per trial

Table 2. Minimum agrometeorological variables recommended for fundamental research rice-weather experiments.

	Instrument
1. Radiation (above canopy)	
Global solar radiation	Moll-Gorczynski type solarimeter
Reflected solar radiation	Inverted Moll-Gorczynski solarimeter
Net (exchange) radiation	Funk type net radiometer
2. Radiation (beneath canopy)	
Bar measure of sunlit area	Bar for measuring sunlit area
Global solar radiation	Tubular type solarimeter
3. Air temp profiles	Ventilated dry- and wet-bulb psychrometer (Pt-resistance thermometer)
4. Water vapour profile	(6 psychrometer units)
5. Wind speed profile	Casella type cup anemometer (6-anemometers)
6. Soil temp profile	Thermocouple thermometer
7. Water temp profile	Thermocouple thermometer
8. Soil heat flux (dryland rice field)	Heat flow meter (3-4 sets)
9. Carbon dioxide concentration	Infrared gas analyzer
10. Dewfall	Dewfall recorder
11. Stomatal resistance	Leaf resistance meter

e. Wind (total run)

3) Recommend that minimum measurements be taken by "Precipitation Stations" on a density of 1 per 200 km^2 (or as modified by recommendations in 1 above). These stations would take the following measurements on a daily basis for near real-time use.

a. Temperature
   1) Maximum
   2) Minimum
b. Precipitation (total)

4) Recommend for small scale modeling for research purposes that a "Principal Climatological Station" be installed at the research location. The measurements from these stations would be on an hourly basis or no less than three measurements per day. Measurements taken would be:

a. Precipitation
   1) Rate
   2) Amount
b. Evaporation
c. Temperature
   1) Soil
   2) Water
   3) Canopy level
   4) 1 meter
   5) 5 meters
d) Solar radiation
   1. Net radiation
   2. Radiation in PAR range
e) Wind - total run and rate
   1. Canopy
   2. 1 meter
   3. 5 meters
   4. 10 meters
   5. 15 meters
f. Wet/dry bulb temperature
g. Dew
   1. Duration
   2. Amount

5) Recommend to the appropriate agency or agencies that methods be developed to gain information on net radiation and radiation in the PAR spectrum from traditional or existing methods of measuring sunshine or cloud data. This radiation information is generally lacking but is a very important component in agrometeorology interpretations.

6) Recommend that feasibility studies be made by WMO, National Meteorology Services, and other appropriate groups for utilizing satellite data as follows:

a. Meteorological satellites

(i) Utilization of existing real-time data

(ii) Utilization of the data to check the quality of climatological stations data for agromet uses.

(iii) Utilize the satellite data to spread meteorological data from climatic stations to more accurately define the weather occurrences between stations and within agricultural regions of interest.

(iv) Recommend that WMO or other appropriate group explore the feasibility of accumulating present satellite data for historical purposes and pursue the establishment of agromet archives in a standard format on magnetic tape. Presently these data are being lost.

b. Landsat satellite

(i) Use the thermomapping capability of future satellites for measurements of soil moisture/plant water status measurements. Such measurements should be given the highest of priorities.

(ii) Make recommendations as to agromet needs during the planning and development stages of new satellites.

(iii) That all satellite data be made available in a digital form on magnetic tape for near real-time utilization.

7) Recommend that WMO coordinate cataloguing services of agromet data so that potential users can go to one source to determine what information is available and in what format.

8) It is resolved that the recommendations of this working group be drawn to the attention of the members of the WMO Task Force on crop/weather models.

Other general recommendations

1) Because of the relevance of the subjects covered, it is recommended that the working group conclusions obtained at the FAO Expert Consultation on Soil-Crop-Weather Relationships (Canberra, May 1977) be published and widely distributed.

2) It is recommended that the attention of the WMO Working Group (when established) should be drawn to the importance of the study of the influence of meteorological conditions on diseases and pests. Consideration should be given to the acquisition of such information which may facilitate the understanding of the influence of weather patterns on their occurrence and distribution, with a view to forecasting their incidence.

3) Rice production is often affected by catastrophic events such as typhoons and floods. It is recommended that WMO bring to the attention of the Typhoon Committee, the Hurricane Committee and the Cyclone Committee, the need for special studies on mitigating the effects of the catastrophic events on rice production (e.g. management, plant-breeds, etc.).

Closure of the session

Dr. Baier summarized the scientific papers presented to the session and highlighted the conclusions and recommendations reached at the working group session.

Dr. Baier took the opportunity to thank WMO and IRRI for organizing the symposium. He specially thanked Dr. Brady, Director General of IRRI, for taking personal interest in the organization of the Symposium/Planning Meeting and for his valuable advice during deliberations of the working group meetings. He thanked all the participants for their excellent contributions and the chairmen of the working groups for their hard work.

Mr. Krishnamurthy, speaking on behalf of the Secretary-General of WMO, thanked IRRI for co-sponsoring the symposium and offering the hosting facilities. He thanked all the participants for their co-operation and understanding and for the excellent conclusions reached.

Dr. O'Toole thanked all members of IRRI who contributed in one way or another to the success of the symposium.

Dr. Brady, Director General of IRRI, expressed satisfaction at the outcome of the symposium. He thanked WMO for their co-operation in the organization of the symposium and expressed hope that WMO would take follow-up action without much delay. He wished the participants a safe return home.

Dr. Baier closed the meeting at 12:30 p.m. on Friday.

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Dr. Baier closed the meeting at 12:30 p.m. on Friday.