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9. ABSTRACT

The second section of papers from the Airlie House conference of 1975 includes three papers on the productivity of international agricultural research systems. The first paper (by Dana G. Dalrymple) documents the impact of the CIMMYT and IRRI varietal developmental programs on wheat and rice production in Asia. A second paper (by Robert E. Evenson) reviews the history of cycles in research productivity and in international diffusion patterns for three commodities: sugarcane, wheat, and rice. A third paper (by Robert E. Evenson) presents measures of the rates of return to the resources invested in research at IRRI and CIMMYT. The fourth paper (by Yoav Kislev) develops a theoretical model of applied research consistent with the historical experience reviewed in the first two sections of papers from the conference.

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Resource Allocation and Productivity in National and International Agricultural Research

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and
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Editors

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Preface

Within the last decade significant steps have been taken to narrow the agricultural technology gap among countries. New international agricultural research centers have been established, and a number of developing countries have made substantial progress in strengthening their national agricultural research capacities. It is estimated that world expenditures on agricultural research (in constant 1971 U.S. dollars) have risen from approximately $4.3 billion in 1959 to $3.8 billion in 1974. In the less developed countries of Latin America, Africa, and Asia, the estimated increase in research expenditures for the same period was from $14 million to $95 million.

The creation of two international agricultural research institutes in the early 1960s was an important factor in the surge of research investment. The establishment of the International Rice Research Institute (IRRI) in the Philippines in 1960 and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1966 signaled a wider contemporary refocusing on research as an essential instrument of agricultural productivity change in the less developed countries (LDCs).

The unsung story is well known. CIMMYT and IRRI developed short-strawed, fertilizer responsive, high yielding, wheat and rice varieties which were rapidly adapted and adopted in parts of Asia, Africa, and Latin America and which produced an upsurge in grain production popularly known as the "green revolution." By 1975, nine international research institutes and two other international programs were either in operation or in the process of being established in the LDCs (see Table 11-1).

The view that effective research capacity in developing countries is a primary means to raising agricultural productivity is now widely shared. The World Bank, the United States Agency for International Development (USAID), and other donors have begun to give agricultural research a higher priority for assistance. Investment in agricultural research in developing countries has grown rapidly in recent years. As the agricultural research system has continued to expand, research productivity and research resource allocation have become important issues for development planners and science managers.

In order to examine these issues, an international conference was held at Airlie House, Virginia, in January 1975. The conference had two main objectives: to examine recent evidence on the returns to investment in national and international agricultural research systems; and to explore the relevance of social and economic factors for the organization and management of national and international research systems. Technical issues related to the measurement of research productivity, the planning of research programs, and the management of research systems were also discussed.

The conference drew together over fifty natural scientists, social scientists, and administrators from national and international research agencies, some of whom were more than one hat. The format of the conference was somewhat unusual. Individual papers were not read but rather circulated before the meeting and only summarized at the conference by prescheduled discussants, several of whose comments proved so stimulating and original that they are included as discussant papers (Nos. 6 and 27). Most of the conference, therefore, was devoted to what turned out to be rich and vigorous discussion.

Following the conference, contributors were asked to review and revise their papers in the light of the discussions. The revised papers were then edited and returned to the authors for their further review, a painstaking process which was completed in November 1975. As they appear in this book, the twenty-eight papers have been organized into six sections. They are preceded by an introduction (by Thomas M. Arndt and Vernon W. Ruttan) which highlights the main issues discussed at the conference.

The first section of this book is devoted to a series of studies of the *productivity of national research systems* in both developed and less developed countries. There are two papers on the organization and productivity of research systems in developed countries: the first (by Yujiro Hayami and Masakatsu Akino) describes the national prefectural system in Japan; the second (by Willis L. Peterson and Joseph C. Fitzharris) discusses the federal-state system in the United States. There are also two papers on returns to investment in agricultural research in developing countries, one drawing upon Colombian experience (by Reed Hertford, Jorge Ardila, Andrés Rocha, and Carlos Trujillo) and one focusing upon India (by A. S. Kahlon, P. N. Saxena, H. K. Bal, and Dayanath Jha). The final paper in this section (by Reed Hertford and

Andrew Schmitz), prepared after the conference, reviews some of the theoretical foundations of, and empirical considerations involved in, the evaluation of returns to research.

The second section includes three papers on the *productivity of international research systems*. The first paper (by Dana G. Dalrymple) documents the impact of the CIMMYT and IRRI varietal development programs on wheat and rice production in Asia. A second paper (by Robert E. Evenson) reviews the history of cycles in research productivity and in international diffusion patterns for three commodities: sugarcane, wheat, and rice. A third paper (also by Evenson) presents measures of the rates of return to the resources invested in research at IRRI and CIMMYT. In a fourth paper (by Yoav Kislev) an attempt is made to develop a theoretical model of applied research consistent with the historical experience reviewed in the earlier papers in the first two sections.

The third section is devoted to the *organization and development of the international agricultural research institute system*. The first chapter (by J. G. Crawford) traces the development of a system for organizing, funding, and managing the new institutes, spearheaded by the Ford and Rockefeller foundations and now guided by the Consultative Group on International Agricultural Research. The programs that have been developed to achieve closer articulation of the research programs of the international and national systems are outlined by the director of IRRI (Nyle C. Brady) and the director of CIMMYT (Haldore Hanson). The problem of establishing effective working relationships between the international and national agricultural research systems is then reviewed (by Sterling Wortman). The final paper in this section (by Burton E. Swanson) presents a comparison of the impact of the IRRI and CIMMYT training programs on the career patterns and effectiveness of young scientists who have studied at these two institutes.

The fourth section is devoted to issues bearing directly on the *organization and management of agricultural research systems*. The first paper (by Albert H. Moseman) outlines the evolution of coordinated national research projects for improving food crop production. Two papers focus on the problem of reorganizing and reforming national research systems: in the United Kingdom (by Tilo L. V. Ulbricht) and in Brazil (by José Pastore and Eliseu R. A. Alves). Next, the contribution of private sector international agricultural research is described (by S. M. Sehgal), based on the experience of Pioneer Hi-Bred International. A systems approach to research resource allocation is then outlined and evaluated (by Per Pinstrup-Andersen and David Franklin). The final chapter in this section (by C. Richard Shumway) presents a review and evaluation of the literature on formal models and methods for allocating resources in research.

The fifth section examines the role of *economic and social factors in re-*

search resource allocations. The first paper (by Martin E. Abel and Delane F. Welsch) outlines a theoretical model for exploring the relative effects of environmental constraints and commodity mix on research resource allocation. The second paper (by John W. Mellor) is devoted to an empirical evaluation of the effects of efforts to relate research resource allocation to alternative goals such as labor absorption. In a third paper (by J. P. Ranalho de Castro and G. Edward Schuh) the use of an economic model to establish research priorities, based on Brazilian data, is illustrated. The role of resource endowments and relative prices in inducing the choice of alternative paths of technical change—that is, labor saving versus land saving—is documented (by Hans P. Binswanger). The final paper in this section (by Alain de Janvry) presents a theoretical model of dialectical interaction between technical and institutional change in agriculture which suggests important directions for future research.

The final section is devoted to discussion of the research strategy and management issues that will affect *the future of the international research system* and the productivity of national research systems. The first paper (by A. T. Mosher) is devoted to a discussion of unresolved issues in the evaluation of the international system. A second essay (by Theodore W. Schultz) focuses on the role of economic policy in influencing the prospects for gains from agricultural research. In the final paper (by J. G. Crawford) the policies and problems facing the Consultative Group on International Agricultural Research and its Technical Advisory Committee in their efforts to strengthen national and international research are reviewed.

The papers included in this volume cannot, of course, reflect fully the excitement and challenge of the Airlie House conference. Particularly significant contributions to the discussions were made also by Richard B. Klein of Cargill Inc.; Joel Bernstein of the U.S. Agency for International Development; John K. Coulter of the Consultative Group on International Agricultural Research; George Dennell, James M. Evansen, Raj Krishna, and Montague Yudelman of the World Bank; M. M. Donald Dow of the National Academy of Sciences; Walter L. Fishel of the U.S. Department of Agriculture; Lowell S. Hardin of the Ford Foundation; W. David Hopper of the International Development Research Centre; Richard Nelson of Yale University; Peter Oram of the Food and Agriculture Organization of the United Nations; S. J. Webster of the Ministry of Overseas Development of the United Kingdom; A. M. Weisblat of the Agricultural Development Council, Inc.; and F. R. Wittenbert of the Parker Pen Co.

The Airlie House conference was given considerable impetus and background by the materials presented and discussed at an earlier symposium on Resource Allocation in Agricultural Research held at the University of Minne-

sota in February 1969. The results of the Minnesota conference, which focused on many of the same issues considered at Airlie House but from a domestic (United States) viewpoint, were published in a book edited by Walter L. Fishel and entitled *Resource Allocation in Agricultural Research* (Minneapolis: University of Minnesota Press, 1971).

Both the Minnesota and Airlie House conferences were oriented to formal research carried out at nonprofit institutions and supported primarily with public or philanthropic funds and, to a lesser extent, to research conducted by private firms. It is recognized, however, that significant technical improvements may also result from informal research by farmers themselves or by small, local firms. Simple selection of improved varieties of seeds has traditionally been an important source of varietal development and yield increase. In the field of mechanical technology, simple but effective mechanical devices invented by farmers or mechanics, such as small irrigation and cultivation equipment, continue to provide many of the models for equipment engineered, manufactured, and marketed by larger firms. The work of both national and international research programs in many cases builds on this indigenous technology. Thus while little is said about informal research in this volume, its potential importance should not go unrecognized.

The structure of public agricultural research differs somewhat between the developed and the less developed nations. In the developed countries, research is conducted both by ministries (or departments) of agriculture and by colleges and universities. In the developing nations, research has traditionally been much more strongly concentrated in specialized arms of the ministries of agriculture or in autonomous, commodity-oriented research institutes. Colleges of agriculture in developing countries have usually concentrated on teaching, although in some cases they have done significant research (the popular rice variety C4-63, for instance, was developed by the College of Agriculture at the University of the Philippines) and may well play a larger role in the future. A paper on "Articulation of the International System with Other Regional Organizations: Ministry and University," by Jose Drilon was originally scheduled for the conference, but unfortunately Dr. Drilon, for reasons beyond his control, was unable to prepare the paper or to participate in the discussions.

We would also like to emphasize that, while this volume focuses on the importance of improved technology in the process of agricultural development, we are quite aware that it is not the only factor. A host of other forces—social, institutional, economic, and technical—both influence the adoption of technology and set the stage for the complex of other changes which must take place in the process of agricultural and economic development. Although improved technology may be the key factor in some societies, in others it may

not. Improved technology alone is clearly not tantamount to agricultural development. But if the proper forms of technology can be efficiently generated through research, the development process can often be facilitated. It is our hope that this volume will contribute to a better understanding of the role of research in the process of technical change and of the role of technical change in agricultural development.

The conduct of the Airlie House conference and the preparation of this volume have been possible only through the help of many individuals and several institutions. The conference planning committee consisted of Robert E. Evenson, Walter L. Fishel, and Vernon W. Ruttan. The conference was sponsored by the Agricultural Development Council under its Research and Training Network Program, a program which, in turn, is funded under a contract with the United States Agency for International Development. Additional support for international participation in the conference was provided by the World Bank.

Turning a set of conference papers by an international cast into a book is, as we learned, far from a quick or simple job. Our task was facilitated by the cooperation and forbearance of the individual authors, most of whom found their carefully revised papers further edited and trimmed. Virginia O. Locke played a key role in the copy editing; her professional skills and contributions were of great assistance. We would also like to express our appreciation to Willis L. Peterson for his review of technical portions of the final page proofs and to Raymond D. Vlasin for his very helpful review and evaluation of a preliminary draft of the conference proceedings manuscript.

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in National and International
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T. M. Arndt, D. G. Dalrymple,
and V. W. Ruttan

7

Evaluating the Impact of International Research on Wheat and Rice Production in the Developing Nations[1]

Dana G. Dalrymple

Research on food crops in or for the less developed countries (LDC's) is relatively new. For decades, much of the agricultural research in LDC's focused on plantation or export crops. Food crops for domestic consumption, with a few exceptions, were largely ignored. The situation began to change in the years following World War II, but even then national research on food crops was usually given low priority and limited funding.

There were some exceptions. Perhaps the best known exception is the cooperative program on food crops begun by the Rockefeller Foundation and the Mexican government in 1943. This work led to new research programs in other Latin American countries in the 1950s.[2] Some other international cooperative research activities were carried out in the same decade, such as the rice hybridization project sponsored by the Food and Agriculture Organization in India. And a few developed nations supported scattered institutional development and research programs in the LDC's. But most of the research on food crops continued to be done in the developed nations. Although precise figures are not available, data compiled by Evenson suggest that, of the total investment in *agricultural* research in 1958, about 90 percent was in the developed nations and approximately 10 percent was in the less developed nations.[3] The proportions spent on *food* crops in the developing nations may have been even less.

A significant change took place in the early 1960s with the establishment

of two international crop research institutes: the International Rice Research Institute (IRRI) in the Philippines and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico. These two institutes were located in LDC's and oriented to their food problems. Their early successes led to the establishment of a number of other international research activities as well as to a rebirth of interest in improving and expanding national research programs. All these activities were enhanced by earlier and concurrent programs of human and institutional development.

As of the mid 1970s, research on food crops in and for the LDC's is finally coming of age. The Consultative Group on International Agricultural Research (CG) – composed of nations, international organizations, and foundations – has been established. The annual investment in international research through this group reached about $47.3 million in 1975. The United States Agency for International Development (AID) contributes up to 25 percent of the costs of CG-sponsored activities and invested $10.655 million in 1975. In addition, AID is actively stepping up financial support for national research programs within LDC's.

Although the funds involved in such projects are substantially greater than they were a few years ago, they are miniscule for the job that has to be done. They are also relatively small in comparison with global expenditures for agricultural research in the developed nations or for other items of public expenditure. Data compiled by Evenson suggest that the total expenditure on agricultural research in 1970 was $1.32 billion in the developed nations and $236 million in the developing nations, or a total of $1.56 billion.[4] The international research funds, however, do represent a significant addition to the total expenditure on agricultural research for developing nations.

Such an investment is likely to spur interest in measuring results. The technical products are abundant and are presented in considerable detail in the annual reports and other publications of the institutes. Economic and social aspects of the resulting technologies are also beginning to be studied in greater detail.

But the quantitative effect of the institutes' efforts on actual production in the LDC's has not yet been closely examined. There are good reasons for this lag: the centers are new, such an analysis is difficult, and few resources have been devoted to the task. Nevertheless, the field is not entirely unexplored. Some studies have been carried out in the past on the effect of national agricultural research programs in both developed and less developed countries. Generally, the results have shown high rates of return to investment in research.[5]

The next step will be a more specific evaluation of the effects of interna-

tional agricultural research. But to do this efficiently will require more than knowledge of economics and quantitative tools. It will also require theoretical and empirical knowledge of (1) the nature of the international centers and the associated international agricultural research system; (2) the adoption process at the farm level for resulting agricultural technology; and (3) available statistical data which help measure both the input into research and the effect of the product.

Some such knowledge exists at present, but it tends to be in fragmentary form. Dr. Robert Evenson and I have been separately involved in analyzing certain components for several years. His attention has been focused on fairly quantitative and aggregative analysis of agricultural research in general.[6] I, on the other hand, have been more concerned with analyzing specific technologies and most recently have been involved in documenting the development, spread, and influence of the high-yielding varieties of wheat and rice.[7]

Both approaches are necessary but not sufficient for evaluating the impact of international research on crop production. There is a need to find a middle ground where quantitative concepts and tools of measurement are more closely woven with empirical knowledge of the technology. And there is a need to blend highly aggregative analysis with studies that are somewhat more local. This chapter moves toward this middle ground.

First we will examine the general question of the various effects of research that must be considered in evaluating its impact, and then we will offer more specific and narrow quantitative analyses of the direct effects on yield and production. A precise and definitive measure of the effect of international research on wheat and rice production is not attempted; this, as will be demonstrated, is most difficult. Rather, conceptual and methodological problems involved in the process are introduced. Empirical data are used largely for illustrative purposes.

Though production changes can have important effects on economic and social factors, these matters were simply beyond the scope of this study. In any case, they have been discussed elsewhere.[8]

Much more work will be needed before the effects of international agricultural research can be comprehensively assessed. This chapter introduces some of the major considerations involved and, it is hoped, will encourage further study of this most important subject.

The International Research Institutes

International agricultural research as defined here consists of work carried out under the aegis of the Consultative Group on International Agricultural Re-

search (CG). As of early 1975, the CG was sponsoring six active international agricultural research institutes, three other institutes in varying stages of development, and three related programs.

Of the six active institutes, only IRRI and CIMMYT have been in operation for more than ten years. Because of the newness of the other four institutes, it is too early to assess their impact on crop production.[9] Consequently, this study focuses on two of the three crops covered by the first two institutes: rice and wheat. Corn is excluded. Research on this crop, for a variety of reasons, has not been as successful as the work on the other two.[10] Any general study of the payoff to research should, of course, include the full range of efforts.

Work leading to the establishment of CIMMYT began in 1943 with the founding of a grain program in Mexico by the Rockefeller Foundation, in cooperation with the Office of Special Studies of the Mexican Ministry of Agriculture. In 1959, Dr. Norman Borlaug became director of the Rockefeller Foundation's International Wheat Improvement Project. The wheat program was merged with a comparable corn program in October 1963 to form the International Center for Corn and Wheat Improvement.[11] By early 1966, "the growing demands on this program by the ever-widening food gap around the world indicated the need for a restructuring and expansion of activities. As a result, the center was reorganized on April 12, 1966, in accordance with Mexican law, as a nonprofit scientific and educational institution . . . to be governed by an international board of directors."[12]

The new board held its first meeting in September 1966 and approved programs for 1967. Major financial support was at first provided by the Ford and Rockefeller foundations. In 1969, AID became a contributor. A new headquarters and laboratory facility were completed at El Batan (forty-five kilometers northeast of Mexico City) and dedicated on September 21, 1971. The initial construction cost of $3.5 million was provided by the Rockefeller Foundation;[13] through 1974, the total capital costs were $6.4 million. (The CIMMYT capital investment did not include housing for the staff. Also, when CIMMYT was legally constituted in 1966 it had acquired a number of vehicles and a fair amount of field equipment; the replacement of this equipment has been charged to operating costs and not to capital.)[14]

In 1959, the Ford and Rockefeller foundations decided jointly to establish a rice research institute in the Philippines, and on April 13 and 14, 1960, when its trustees met for the first time, IRRI was formally organized. Construction was finished in January 1962, and the institute was dedicated on February 7, 1962. By that time the research program was underway. The capital cost was $7.5 million. (This included housing for staff.)[15] Initially, Ford

provided the physical plant and Rockefeller the operating funds; in 1965 they began to split the operating costs. Support from AID was added in 1970.

The growth in the total expenditures of the two institutes is depicted in Table 7-1. One should not, of course, total the columns for the individual institutes without at least making an allowance for inflation. Barker, in cumulating expenditures at IRRI from 1960 to 1972, used a GNP deflator and then went on to include a discount factor equivalent to an interest rate charge for the use of money over the period. The unadjusted total was $24.3 million; allowance for inflation raised it to $28.6 million, and addition of the discount factor increased the total to $51.6 million.[16]

Since the establishment of the centers, their programs have grown somewhat beyond the crops indicated in their titles. On the other hand, some regional rice work has been taken up by the International Center for Tropical Agriculture (CIAT) in Colombia and the International Institute for Tropical Agriculture (IITA) in Nigeria. The total amount proposed for actual expenditure on wheat and rice research in 1975, exclusive of related or overhead costs, is given in the accompanying tabulation.[17] Even if a prorated portion of the other

Institute	*Wheat*	*Rice*	*Total*
CIMMYT	1,166		1,166
IRRI		2,380	2,380
IITA		225	225
CIAT		153	153
Total	1,166	2,758	3,924

Amounts are given in thousands of dollars.

costs were assigned to the two crops and special projects were added, the totals would probably not be over $10 million. The annual total would have been less in previous years. As noted earlier, the work on wheat in Mexico goes back to 1943, but the annual expenditures by Rockefeller were relatively modest. The total annual expenditures on wheat research by the Office of Special Studies for 1954 to 1960, converted from 1958-60 pesos, ranged from $345,000 to $203,000.[18]

Hence, when the impact of the international centers on wheat and rice production in the LDC's is evaluated, the benefits can be compared with a relatively small investment over a short period. In an overall view, the expenditures on research in relation to the annual values of the crops involved are miniscule indeed.

Throughout their history, IRRI and CIMMYT have been closely involved with national LDC programs. As Hardin and Collins have noted, these centers "were not designed to supplant country efforts, but indeed were developed to

Table 7-1. Annual Total Expenditures, both Core and Capital, for IRRI and CIMMYT, 1959-75[a]
(in thousands of dollars)

Year	IRRI	CIMMYT[b]
1959	250[c]	
1960	7,060[c]	
1961	229[c]	
1962	405[c]	
1963	875[c]	
1964	625[c]	
1965	1,055	
1966	1,125	457
1967	1,164	843
1968	1,641	1,427
1969	1,955	2,053
1970	2,135	5,017
1971	2,676	4,836
1972	2,960	4,942
1973	3,084	6,231
1974 (est.)	4,557	5,563
1975 (proposed)	8,520	6,834

Source: For 1959-64 (IRRI), letter from Faustino M. Salacup, executive officer and treasurer, IRRI, August 28, 1974. For 1965-69 (IRRI), Werner Kiene, Ford Foundation, August 1974. For 1966-71 (CIMMYT), "This is CIMMYT," CIMMYT Information Bulletin no. 8, March 1974, Chart 15/2, Tables 1 and 2. (Table 1 lists donors but really means expenditures [letter from Robert D. Osler, deputy director general and treasurer, CIMMYT, September 11, 1974].) For 1970-75 (IRRI), 1972-75 (CIMMYT), budget submissions or presentations for each center for 1974-75, Table III.

[a] Except as noted, data refer to actual total expenditures. In most of the source tables for 1970-75, this category is referred to as "application of funds" (exclusive of funds carried over to the following year). It includes, in addition to funds obtained from the Consultative Group (CG) or individual donors before 1972, three other sources of "income": earned, indirect, and unexpended balances from the previous year. The totals therefore exceed, by these amounts, the annual funding requested from the CG. The totals exclude working capital and funds received and spent on special projects.

[b] The International Center for Corn and Wheat Improvement was first formed in cooperation with the Mexican government in late 1963 but was then reorganized and reestablished on an international basis as CIMMYT in 1966.

[c] Grants received for capital and operating costs; not actual expenditures.

complement and stimulate national research programs."[19] The nature of these institutional ties is amply described in the annual reports of the centers and in other papers.[20]

Relating Research Results and Production Changes

It is a long way from the international agricultural research institute to the farmer's field. Relating the activities of the institute to actual changes in crop production requires an understanding of (1) the potential effects of research and (2) the reasons for the gap between potential and reality. To judge the results of international research in terms of farmers' yields is to judge many other aspects of the rural economy as well. It is a severe test.

Potential Effects of Research

The major product of the international institutes is new technology, which, in turn, brings about changes in the production process for the commodity involved. The direct quantitative effects are that (1) output is expanded at the same overall cost, (2) the same output is produced at lower cost, or (3) there is some combination of these two results. Direct effects may also be accompanied by indirect effects.

Direct effects of the HYV's. High-yielding varieties (HYV's) of wheat and rice are best known for their effect on the quantity of output. In addition, they may also influence the quality of the product.

HYV's usually bring about increased output per unit of land. While yields are increased, so are the total costs per unit of land, because a package of associated inputs is needed. However, if HYV's are properly sited and used, returns per unit of product are usually increased. A recent example is Sidhu's study of wheat in the Punjab of India, which revealed that unit costs of production with the new varieties declined about 16 percent.[21] This increased profitability is, of course, largely responsible for the widespread adoption of the HYV's.

Yield potential is increased largely because of the semidwarf characteristics of the varieties. Additional fertilizer tends to be reflected in increased yields rather than in increased vegetative growth. The short, stiff straw of these varieties also means that they are less likely to lodge (fall over).

Although HYV's, given the proper package of inputs, usually have a clear yield advantage over traditional varieties, it is difficult to measure the difference precisely. The improvement is not the same for wheat and rice. And advantages vary widely within each crop, depending on the degree to which the recommended level of inputs is used, the quality of the land base, and a host of other factors.

In the late 1960s, multiples of two or three times the traditional yield were claimed for the HYV's. These were largely measures of *potential* taken from experiment station trials or supervised demonstration plots. In itself, this increased potential could be considered one possible measure of the fruits of international research. Actual farm yields, however, have been lower. Some of the reasons for this difference will be outlined later in this chapter.

The yield effect has taken two different patterns in the breeding programs for wheat and rice.[22] Semidwarf wheat varieties were developed in the second stage of the Mexican breeding program and were first released in the early 1960s. The semidwarf characteristics were part of the IRRI rice-breeding program from the outset. As a result, the yield potential of the newer Mexican wheat varieties, which incorporate the dwarfing characteristic, is greater than that of the earlier improved varieties, while the maximum yield potential of the IRRI varieties has not increased greatly since the introduction of IR-8.

These different patterns were partly related to problems of disease. The major problem for wheat was rust (a moldlike fungus). Development of resistant varieties was considered to be the only answer, and Borlaug took up this work in 1945. By 1949, four new varieties were developed which were soon widely planted. The battle is a continuing one, however, because rust is extremely persistent, appearing repeatedly in new strains.[23] In 1974, CIMMYT reported that, although the wheat varieties that moved out of Mexico in the 1960s showed good resistance, "resistance to some of the rusts is now breaking down. New varieties with different genetic resistance are urgently needed. It appears that 10 years may be the longest period that a variety can withstand the constantly changing attack of the three rusts."[24]

Disease was not an important factor in the early IRRI activities, but it soon became a serious concern. Other problems receiving major attention include insect resistance and tolerance for such stress factors as drought, cold, deep water, and soil problems.

In addition to looking for increased yield *potential*, the institutes are placing considerable emphasis on achieving yield *stability*. Resistance to insects and disease and tolerance for environmental stress factors play a major role in reducing year-to-year fluctuations in production. In pursuing yield stability, CIMMYT is making a number of crosses between spring and winter wheats and between wheats and other cereals. IRRI has established the Genetic Evaluation and Utilization Program which seeks to develop varieties with improved resistance and tolerance. As a result of this search for yield stability, the potential geographic area of varietal use may be broadened.

Some of these research efforts will produce higher average farm yields, but other research will be needed just to maintain these higher yields in the face of ever changing attacks from insects and disease. Such maintenance research,

although absolutely necessary, may not show up well in conventional measures of productivity.[25] Increased yield stability, however, may be viewed by farmers as a reduction in risk and hence could lead to a subsequent increase in agricultural output.[26] Since maintenance research may become increasingly important as agriculture becomes more complex, it is vital that further attention be given to its measurement.

The new varieties differ qualitatively from traditional varieties in two primary ways: consumer acceptance and nutrient composition. Some of the early institute wheat and rice varieties achieved only limited acceptance in certain areas because of color, appearance, or taste differences. The result was a lower price. Most of these problems were taken care of in subsequent breeding programs, though traditional varieties still may be preferred in some places.

The question of relative nutrient quality is more difficult to assess. It depends on an involved interplay of genetic makeup, quantity and timing of nitrogen applications, and environmental factors. Although on balance there may not be much of a difference between the HYV's and the traditional varieties, an attempt is being made, particularly with rice, to breed in higher protein levels or quality.[27] The challenge is to find varieties which have both higher yields and higher nutrient levels.

Indirect effects of the HYV's. The indirect effects of the HYV's, like the direct effects, may have important quantitative and qualitative dimensions. Both of these dimensions are often overlooked.

One of the major biological features of the HYV's, especially rice, is their photoperiod insensitivity, which often shortens the time needed to reach maturity, thereby providing greater flexibility in planting dates. This helps make it possible to grow an extra crop a year in some regions. Several rice-eating nations in Southeast Asia have recently requested CIMMYT's help in introducing a wheat crop during the winter season. And Pakistan is studying the possibility of growing two crops of wheat a year. For these reasons, multiple cropping usually increases in green revolution areas. Castillo notes that in Asia adoption of the modern varieties "is almost synonymous with the adoption of multiple cropping" and that in some cases where their yields were not superior to local varieties "they were adopted nevertheless because of the shorter growing period."[28] Perhaps, in the long run, this indirect effect on output will be as important as or even more important than the direct influence on yield.[29]

A second indirect effect is that higher yields may free resources for other uses. This was recently reported to be the case in Uttar Pradesh in India, where "the coming of the new technology has freed the small farmer from the less

profitable cropping patterns on which he could always depend to provide minimum quantities of such staples as wheat and animal fodder for home consumption. If he grows high-yielding varieties, the small farmer can supply his home consumption needs and still have land remaining to grow high-yielding cereals for market or other high-profit crops like sugarcane."[30]

To take these and other effects into account we should increasingly turn our attention from yields *per crop* to yields *per unit of land per year*. This will be particularly true as more work is devoted to developing improved farming systems.

The research on wheat and rice can have many economic and social effects, in addition to its effects on production. But measurement of the effects of research on output – detailed in later sections of this chapter – is a necessary and often missing link in the chain of analysis.

The Gap between Potential and Reality

High-yield technology developed at the research level simply reveals the potential for improved yield; this potential must be transformed into reality in actual farmers' fields in the LDC's. However, many factors outside the control of the experiment station – such as biological and economic constraints or traditional farming methods – may interfere with the optimal use of HYV's.

Nature of the institute product. The new varieties are generally high yielding only if accompanied by a package of inputs. Chief among these are fertilizer and improved management, but both water and control of insects and diseases may also be vital. The international center may provide, along with the seed, a set of recommendations for such inputs but these must actually be applied by the farmer at the local level. Many forces beyond the farmer's control can affect the availability of some of these inputs, as has recently been shown for fertilizer. And other factors, such as the availability of credit, influence the farmer's willingness to actually use the inputs.

In many cases, the HYV provided by the institute is only raw material which needs to be refined for local use by national research programs. It is instructive that CIMMYT does not release varieties as such but rather "distributes germ plasm to national programs" leaving "governments . . . free to release them as varieties under local names or . . . [to] use CIMMYT germ plasm in their own breeding programs. Either way, the national programs take responsibility for what is selected and released."[31] Similarly, IRRI varieties have been reissued under other names and/or extensively crossed with local varieties in national programs.[32]

Another complicating factor in measuring research efforts is that some varieties included in the HYV category were developed in national programs

either before the centers were established or independently of them. In fact, the IRRI and CIMMYT varieties are not wholly new varieties; in most cases, they build on generations of breeding efforts which have gone on before at the national and regional levels.[33] For these reasons, the new wheats and rices should be viewed as joint products of national and international research efforts. This makes it difficult to distinguish the particular contributions of the institutes and hazardous to attempt, as Evenson has done, to sort the HYV's into the three groups of "institute-bred," "joint institute-national," and "other independent" (see chapter 9). Such a breakdown is further hindered by the lack of information on discrete varieties in HYV data from many countries.

Constraints on realizing potential. The yield potential of HYV's determined on experiment stations is often several times higher than that obtained in practice. In the Philippines, for instance, the potential rice yield is in the neighborhood of eight metric tons per hectare, whereas actual overall yields (traditional and HYV) are slightly less than two tons.[34]

What accounts for such differences? First, the HYV's are not planted on all of the crop land. In Asia in 1972-73, the HYV's accounted for about 35 percent of the total wheat area and 20 percent of the total rice area. In a few nations the proportions were relatively high: for wheat the HYV proportion was 55.9 percent in Pakistan and 51.5 percent in India; for rice the HYV proportion was 56.3 percent in the Philippines and 43.4 percent in Pakistan.[35] Data on trends are provided in Figure 7-1.

Second, even with local breeding efforts, there are biological limits on the proportion of crop area suitable for the HYV's. For instance, much of the wheat area in Turkey is suited only for winter wheats, whereas the Mexican HYV's are spring wheats. Within an area planted to HYV's, numerous other biological problems restrain output. A breakdown of the constraints reported in one small sample rice survey in the Philippines in 1972-73 suggests the variety of possible limitations that face the farmer.[36] (See accompanying tabulation.) Some other factors restraining HYV adoption may be classified as institutional/economic and risk/uncertainty.[37]

Limiting Factor	*Dry Season*	*Wet Season*
Insects and diseases	35%	70%
Water	26	
Nitrogen	21	6
Weeds	9	18
Seedling	9	6
Total	100%	100%

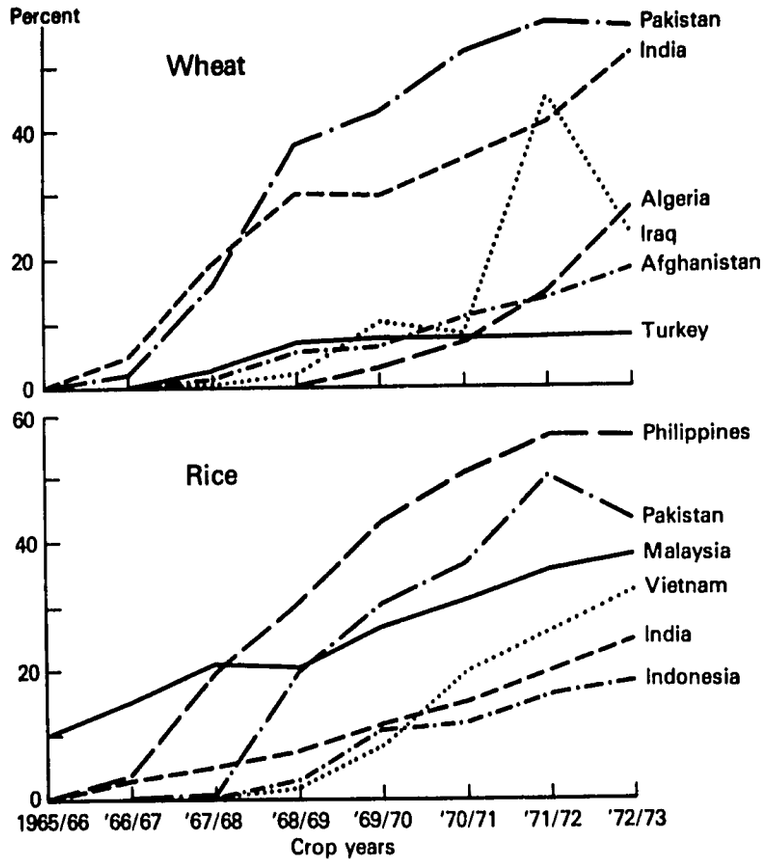


Figure 7-1. Proportion of total wheat and rice area planted to high-yielding varieties, 1965/66-1972/73.

But even if these factors are taken into account, HYV yields are often not as high as might be expected. This is partly because many farmers do not follow the recommended practices for levels of input use. The Philippine survey noted above illustrates the difference in rice yields (in metric tons per hectare) owing to farmers' practices.[38] (See accompanying tabulation.) A num-

Practices	*Dry Season*	*Wet Season*
Recommended	7.3	5.0
Farmers	3.9	3.3
Difference	3.4	1.7

ber of other studies have shown that many farmers either do not use recommended practices or do not use them at recommended levels.[39] There are many reasons for this less than complete usage; in some cases continuation of traditional practices represents a rational allocation of resources under the financial, price, and other conditions at the farm level. Moreover, in measuring increased yield and production at the national level it is impossible to know precisely to what extent the recommended inputs have actually been used.

We see, then, that the gap between potential and reality may be partly reduced by greater use of improved practices. And the effects of some biological factors can eventually be modified through research – for example, by developing greater insect and disease resistance. But there are technical and economic limits to how far this process will go, and there will always be some gap between potential and reality.

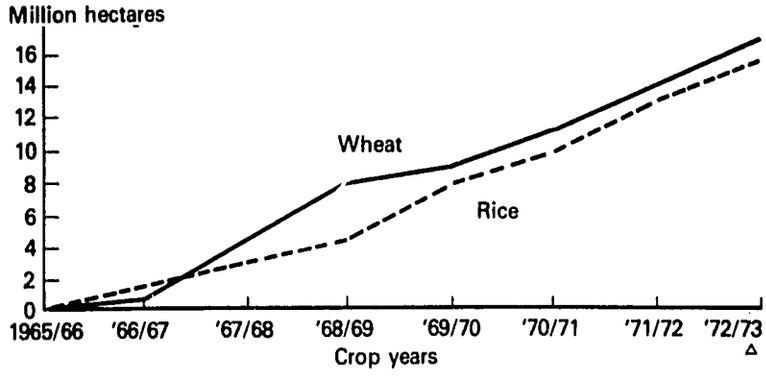
Thus, beyond the varieties themselves there are many factors involved in the realization of higher yields at the farm level. To measure the productivity of the international institutes themselves on the basis of productivity at the farm level necessarily involves the measurement of such other factors, which range from the effectiveness of the national research agency, to the price of fertilizer, to the weather.

Changes in Area and Yield

Changes in crop production are usually a function of changes in area and/or yield. Improvements in technology are reflected, for the most part, in increased yield. New technologies are less often needed for expansion of area. Thus, in initially evaluating the effect of the HYV's on production, it is useful to determine the relative importance of changes in area and yield.

Increased yields may be caused by many factors. Technology is only one such factor, and the HYV's are only one form of technology. Still, we can gain an impression of the importance of HYV's by comparing changes in HYV adoption and changes in production and by examining relative yield levels of the HYV's and of the traditional varieties. Examining relative yields will also provide the basis for the more sophisticated analysis of the effect of the HYV's on production which we undertake below (see "Measuring Impact on Production").

Data on area planted to HYV wheat and rice in developing nations go back to 1965-66, the first year the varieties produced by the research institutes began to be used internationally to any degree. The data now available extend through 1972-73. It is often not possible to separate the institute varieties in direct use from their progeny and from other improved varieties, so they are all generally lumped together.



ΔPreliminary.

Figure 7-2. Estimated high-yielding wheat and rice area, Asia and North Africa, 1965/66-1972/73 (excluding communist nations).

HYV data for noncommunist LDC's are depicted in summary form for the 1965/66-1972/73 period in Figure 7-2. Area devoted to the HYV's has expanded sharply, but it is still concentrated in Asia, with some HYV wheat in North Africa and some HYV rice in Latin America. Comparable data are not yet available for communist nations.[40]

Total area planted to all types of rice can be obtained for these countries from data compiled by the Foreign Agricultural Service of the USDA or by the Food and Agriculture Organization of the United Nations. Deducting HYV area from the total area gives us, of course, the area planted to regular varieties.

Information can be found on total wheat or rice output for nearly all countries. If the area planted to wheat and to rice is known, it is obviously possible to calculate the average yield for all varieties. However, calculation of relative yields of the HYV's is more difficult. In a few cases, the production and yield of HYV's is reported separately. But more often HYV yields have to be pieced together from a variety of sources.

Effect of Changes in Area and Yield

In assessing the impact of HYV's, some observers look merely at trends in total wheat or rice production in a particular LDC. This procedure alone is inadequate for the measuring of impact because it does not take into account relative changes in area and yield.

Nature of area and yield expansion. There is little information available about

the effect of the HYV's on the total cropped area. Considering their biological requirements, it is unlikely that much new land has been cleared for their use. Instead, they have probably substituted for existing crops on the better land. The question then is whether they have substituted for a traditional variety of a like crop or for other crops. It appears that they generally replace like crops, but this is not always the case, especially on irrigated land.

Area trends in India from 1967/68 to 1973/74 reveal different patterns for wheat and rice. For wheat, there was fairly significant expansion of the total area. On the other hand, total rice area expanded only slightly.[41] This suggests that the expansion of HYV wheat involved some replacement of other crops, while the HYV rice area appears to have substituted largely for traditional varieties. Much of the new wheat area would otherwise have been left fallow or planted to chickpeas or other crops. The specific sources of wheat area in 1970-71, compared with those in 1963-65, are presented in the accompanying tabulation.[42] In the Punjab barley, gram, and cotton were the crops replaced by wheat.[43]

	Percentage
Land already in wheat, 1963-65	68.3
Land shifted out of gram (chickpeas)	14.7
Land from fallow or other crops	17.0
Land in wheat, 1970-71	100.0

Relatively little analysis has been made of comparative yield data at the national level. The catch here is the word *comparative*: while we have data on yields where HYV's and traditional varieties are planted, we usually do not have a comparison of the resource base. HYV's are normally planted on the best land. But when they are more widely planted, presumably expanding into less suitable land, yields drop off.

Differentiating area and yield effects. The first step in differentiating the effects of changes in area and yield might be to calculate these changes for countries that have adopted HYV's to a significant extent over a given period of time. For our purposes, averages of two four-year periods, 1960-63 and 1970-73, have been tabulated. The comparisons are conservative in that 1972 was generally a poor year. Countries selected were those where 12 percent or more of the wheat or rice area was planted to HYV's from 1970/71 to 1972/73. Two countries in this classification were omitted: Nepal, because estimates of total wheat areas, yield, and production vary, and South Vietnam because of the influence of the war.

Both area and yield were expanded in each country (see Table 7-2), but in every case except that of Malaysia the relative increase was greater for yield

Table 7-2. Relative Increases in Production, Area, and Yield for Wheat and Rice, 1960-63 to 1970-73

Crop/Country	HYV Proportion 1970/71-1972/73	Increase in 1970-73 Average over 1960-63 Average		
		Area	Yield	Production
Wheat				
Pakistan	52.3 to 55.9%	+ 22.3%	+ 45.2%	+ 77.8%
India	35.5 to 51.5	+ 38.2	+ 56.1	+ 115.7
Rice				
Philippines	50.3 to 56.3	+ 0.4	+ 33.9	+ 34.2
Pakistan	36.6 to 43.4	+ 22.8	+ 73.3	+ 112.9
Malaysia	30.9 to 38.0	+ 43.7	+ 16.5	+ 67.2
India	14.9 to 24.7	+ 4.6	+ 13.8	+ 19.3
Indonesia	11.2 to 18.0[a]	+ 18.8	+ 29.1	+ 53.4

[a] Government programs only. Additional HYV area planted in private plots.

than for area. The increase in yield ranged from 1.5 times higher than the increase in area for Indian wheat and Indonesian rice, to 2 times for Pakistan wheat, and to 3 times for Pakistan and Indian rice. In the Philippines, virtually all the increase was in yield.

Given this data, it is possible to assess the relative importance of area and yield expansion more formally, as is done in Table 7-3. Increases in yield accounted for a significant portion of the expansion in production in six of the seven cases cited and were of moderate importance in the seventh. Yield increases accounted for virtually all the expansion in rice production in the Philippines and from 50 to 74 percent in the other five cases. Malaysia is the only country where area expansion was more important, and this may have been the result of the addition of some major irrigation projects.

Thus, although both area and yield expansion were involved in production increases in seven cases (five countries) where substantial areas were planted to HYV's, growth in yields generally appeared to be more important.

Annual Changes in Yield

It seems that yield increases were an important factor in production increases in areas where HYV's were planted. What, then, did the annual changes in overall yield patterns look like? How did they differ between HYV's and traditional varieties?

Overall changes in yield. Changes in national wheat and rice yields for the countries noted in the previous section are depicted in Figure 7-3. The following trends are apparent.

Yields in wheat were relatively steady in India and Pakistan through 1967

Table 7-3. Roles of Area and Yield in Production Expansion, 1960-63 to 1970-73

Crop/Country	Production Increase[a] Owing to Expansion	
	Area	Yield
Wheat		
Pakistan	35%	65%
India	42	58
Rice		
Philippines	1	99
Pakistan	27	73
Malaysia (W)	70	30
India	26	74
Indonesia	40	60

Source: Formula and calculations by Robert Niehaus of the Economic Research Service, USDA.

[a] Calculated according to the following formula:

$$1 = \frac{\log(1 + a)}{\log(1 + p)} + \frac{\log(1 + y)}{\log(1 + p)}$$

where a, y, and p are the percentages in Table 7-2 (but carried out several decimal places in some cases).

and then rose sharply in 1968. Yields in India continued to rise through 1972 but dropped in 1973. Pakistan's yields moved up more slowly but continued to rise in 1973, exceeding those of India.

Yields in rice either remained about the same or rose only gradually through 1966 and 1967. After 1968 Pakistan and Indonesia showed the sharpest and most persistent gains. Though yields in the Philippines appear to have increased only very gradually, changes in accounting and reporting systems may have influenced some of these data. India has shown only a gradual increase over the period. Yields dropped in three of the four countries in 1972 but increased in all of them in 1973. Malaysia was not included on the chart simply because its yield levels averaged above the upper bound. (Malaysia showed no particular trend from 1960 to 1967, but levels moved up substantially in 1968 and 1969; more moderate increases were registered in 1971 and 1973.)

Not surprisingly, these yield trends coincide roughly with the expansion of the HYV area in each country shown in Figure 7-1 (except for the drop in the Philippine rice yields in 1971 and 1972). The impact, however, seemed to be least for rice in India—probably because the HYV area represented only a small proportion of the total area, and because the HYV's used in India have

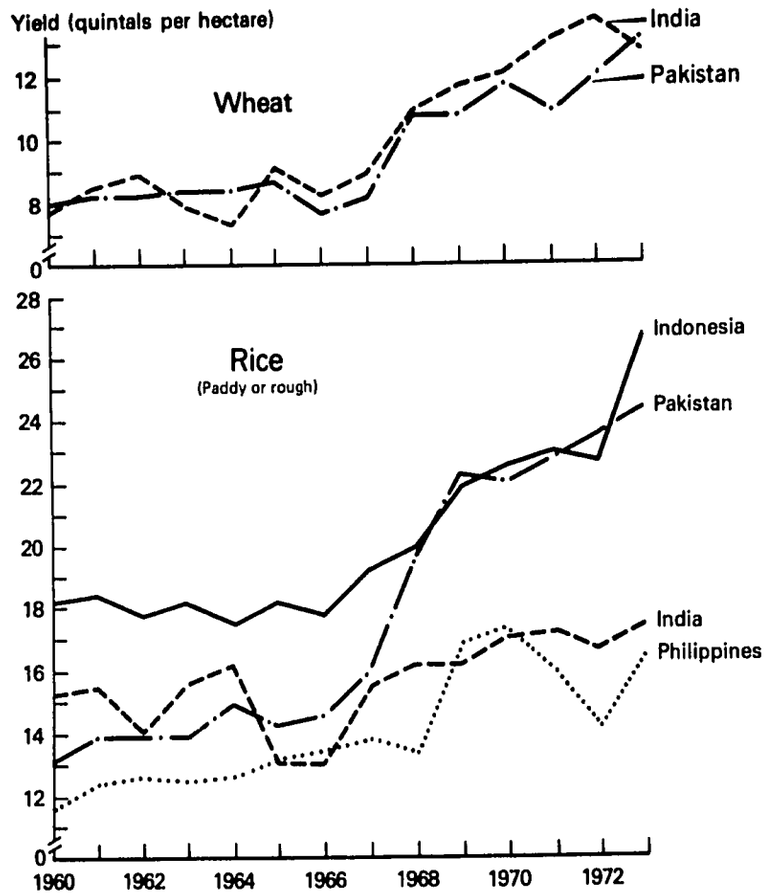


Figure 7-3. Trends in wheat and rice yields, 1960-73.

not yet proved to be well suited to local monsoon conditions. Other factors beside the HYV package, of course, may well have had some influence.

Comparative yield levels. Some national data are available which give an idea of the yield levels of the HYV's compared with those of traditional varieties. These data can be misleading because, as noted earlier, the HYV's are usually planted on the better land. Even so, it may be of interest to review the official statistics and to compare them with other measures.

A few official national statistics have been gathered. One USDA report

summarized these figures for wheat from 1966 to 1970 for India, Pakistan, and Turkey.[44] It revealed that HYV yields were substantially above local varieties – from 1.77 to 3.70 times as great; that as area planted to HYV's expanded, their yield levels dropped, though not evenly; and that as HYV area expanded, national yield levels increased. These relationships would be expected. Because they produce higher yields, HYV's account for a larger proportion of total production than of total area. The difference in proportion, however, decreases as the average HYV yield level decreases over time.

Similar data are available for wheat and rice in India for the period from 1966/67 through 1973/74 (Figure 7-4).[45] They show the same general trends noted above, with a few variations. In India, yields for HYV's ranged from less than two to more than three times as high as those for traditional varieties. The wheat multiple was consistently higher than the rice multiple, though the difference narrowed later in the period. These ratios of HYV to traditional yields were fairly consistent through 1970/71 and then dropped. (See accompanying tabulation.) In the Philippines, official estimates for rice

Crop Year	*Wheat*	*Rice*
1966/67	2.87	2.58
1967/68	3.70	2.18
1968/69	3.49	2.05
1969/70	3.68	2.26
1970/71	3.44	2.27
1971/72	2.50	2.03
1972/73	2.35	1.76
1973/74 (prelim.)	2.59	1.71

over the 1968-72 period suggest that HYV yields averaged from 1.30 to 1.35 times higher than those of traditional varieties (including upland).[46]

If the land base were standardized, the comparative yield levels cited above would be somewhat lower. Several years ago I assumed – when pressed for a rough estimate – that the HYV package in irrigated areas might result in a relative yield ratio of 2.0 for wheat and 1.25 for rice. The ratios would be lower in unirrigated areas.

Unfortunately, it has not been possible to review enough studies to provide a good empirical check on these estimates. Two recent investigations, however, provide both larger and smaller multiples for rice, suggesting that the above figure may not be far off the mark as an average. A study of rice production at the village level in six Asian nations in 1971-72 revealed that the overall multiple for both wet and dry seasons was somewhat higher: 1.32 to 1.33.[47] Somewhat lower ratios were obtained in the Philippines for the period from 1968 to 1972 when the national data reported previously were sorted out by type of land base. The HYV advantage was 1.14 on irrigated

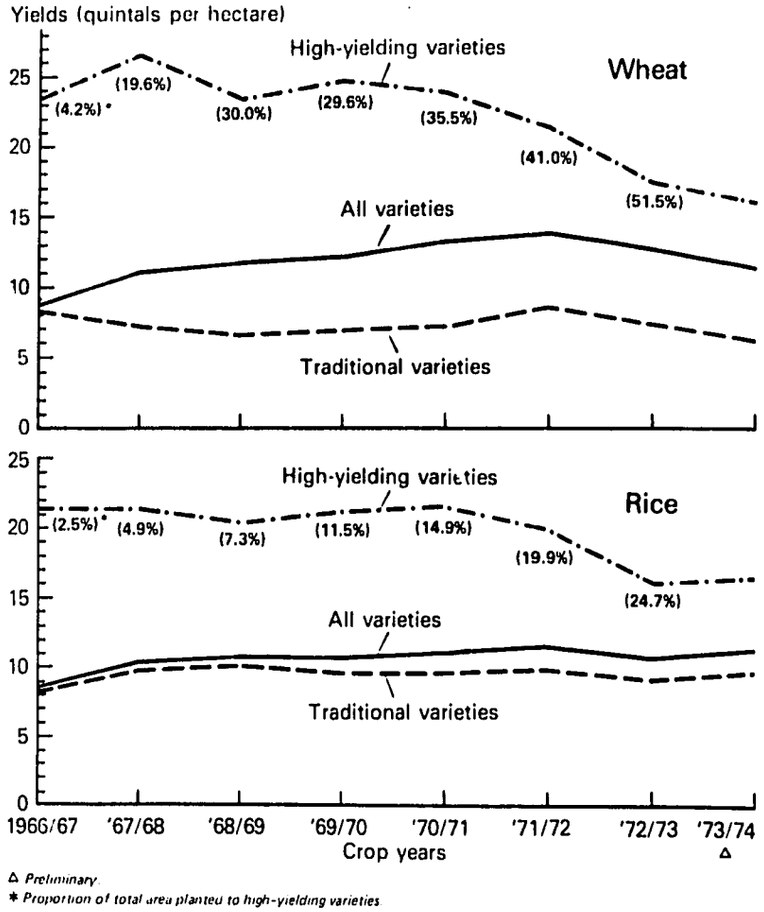


Figure 7-4. Trends in yields for traditional and high-yielding varieties of wheat and rice, India, 1966/67-1973/74.

land and 1.03 on rainfed lowland.[48] Most HYV's are raised in irrigated areas. The multiple did not show any pronounced decline over the period; perhaps the arrival of improved varieties compensated for the possibility that lower quality land may have been planted to HYV's.

For wheat, the countries cited have made extensive use of irrigation. A preliminary review of the data for dryland wheat production in North Africa and the Near East does not yet show a clear pattern of yield increase. This

may be because levels of adoption are still relatively low, but may also reflect (1) the impact of lower water levels and of variations in rainfall, and (2) the fact that the traditional varieties in some of the North African nations really are improved varieties which were introduced over the twentieth century and in some cases have characteristics and ancestry similar to the Mexican varieties.[49]

Numerous other data could undoubtedly be found; the difficulty is to distill a meaningful average from them.

Obviously we need to know much more about actual yields at the farm level before we can make precise evaluations of the contribution of the HYV's or of the HYV package to increased yields. And we need to know much more about the influence that various purchased inputs, the weather, and other factors have on production.

Measuring the Impact of Technology on Production

The next step in analyzing the impact of the new technology is to evaluate its effect on production. The main problem we face is that a great many different factors influence changes in production. Furthermore, we do not know precisely what production would have been in the absence of new technology.

To measure production changes, most economists would use (1) a production function, or (2) an index number approach.[50] Each technique has its advantages and limitations. This section presents first a brief review of both techniques in the context of wheat and rice production and then a simplification of the index number technique. Finally, the findings of these two approaches are compared.

Production Function Analysis

A production function is a form of multiple correlation (or regression) analysis in which changes in production are treated as a function of variations in a number of input variables. The variables might include, as Evenson has suggested, (1) utilization of land, (2) fertilizer, (3) irrigation, (4) other agricultural inputs, and (5) some measure of the introduction of new technology, such as the percentage of the crop produced from the new varieties.[51]

Data requirements. Although a logical functional form can be fairly easily laid out, the problem is to obtain statistical data for each of the input variables. This can be accomplished at local or regional levels by farm surveys, but it is a very difficult task at the national level. About the only information readily available is the HYV area. Fertilizer is of critical importance, yet no LDC reports regular national data on the amount of fertilizer applied to individual

crops such as wheat or rice, let alone to HYV's. All that is reported on an annual basis is the amount of fertilizer apparently consumed on all crops (these data are presented in FAO's annual *Fertilizer Review*). Some export or nonfood crops are large users of fertilizer. The use of insecticides and pesticides is even less clear. Irrigation is not such an unknown, but it varies a great deal in quality and we have only a vague idea of the amount of irrigated land devoted to HYV's.

Even if these data were available, we would have to take other variables into account. Perhaps the most difficult to measure is weather. While there have been sharp changes in weather since the mid 1960s – and 1972 was particularly bad – there are apparently no indexes which adequately measure the total yearly changes in weather. Perhaps over a long enough time period these changes would balance out, but the period at hand is only eight years long. Some national data are available which make a start possible, such as the all-India rainfall indexes,[52] but they are only a partial means of measuring the weather.

A more easily measured variable is the change in the price of both the product and the various inputs. Increased product prices and lower input prices would be expected to increase the adoption of innovations. Such changes have taken place in the prices of rice and urea. The cost of irrigation water depends on the source but so does quality (in terms of when it is available); canal water is usually much cheaper than tubewell water, but the timing of the application of tubewell water can be regulated much more closely.

All these factors, as well as others, should be considered in specifying a production function – but this is much easier said than done.

Two recent analyses. Despite these problems, many production function analyses have undoubtedly been conducted. Two recent studies on wheat and rice may be representative. One was done at a very broad level, whereas the other was conducted at a regional level within one country. Both used Cobb-Douglas production functions.

Robert Evenson recently reported on a highly aggregated analysis for wheat and rice for Asia and the Middle East.[53] He first considered a country-by-country analysis, but because the data were limited he focused on a regional grouping, using one group of countries for wheat and another for rice. Fertilizer was measured by its total use on all crops, and the HYV areas were based on my earlier area compilations.

The analysis was carried out in two steps. In the first stage, production was expressed as a function of crop area, total use of fertilizer, and the proportion of crop area planted to HYV's. In total, these variables explained nearly all the variation in wheat and rice production. Though each variable was signifi-

Table 7-4. Increase in Production and Value Associated with the Use of High-Yielding Varieties, Asia and Mideast

Crop Year	Production (%)		Value (million dollars)	
	Wheat[a]	Rice[b]	Wheat[c]	Rice[d]
1965/66[e]				
1966/67	0.5	0.5	30	76
1967/68	2.8	1.6	170	233
1968/69	5.2	2.8	325	420
1969/70	5.4	4.6	340	695
1970/71	5.9	6.0	403	905
1971/72	6.7	7.7	445	1,155
1972/73	7.4	9.0	523	1,359

Source: Revised data reported by Robert Evenson, chapter 9 in this volume, Table 9-2; letters from Evenson, September 29, 1975, November 19, 1975.

[a] Thirteen countries.
[b] Twelve countries.
[c] Wheat priced at $75 per metric ton.
[d] Rice priced at $100 per metric ton.
[e] Figures negligible.

cant, crop area was the most important. It was surprising that such a crude measure of the use of fertilizer was significant, but it was not surprising that overall crop area was more important than the HYV area, since the latter was of some magnitude only late in the period. In the second stage of Evenson's analysis, he introduced a number of other measures of research. The results with respect to the variables discussed above were roughly similar.

From this two-stage analysis Evenson concluded that "while the high-yielding varieties did contribute very significantly to increased production, they were by no means the sole source of productivity gains in LDC agriculture."[54] Besides the HYV's and fertilizer, other important reasons for growth in productivity were indigenous research findings and borrowed research discoveries. Whereas two studies revealed (as has been suggested earlier) that the superiority of the HYV's declines as their portion of the total area planted increases, a subsequent and more refined analysis indicated that this decline could be offset to a considerable degree by indigenous research which modifies the technology to suit local conditions.[55]

Evenson went on to calculate the increase in wheat and rice production in the countries studied and then converted this to value terms (Table 7-4). His calculations have gone through three stages of refinement; the third stage is reported here.[56] Even if the figures are only roughly accurate, they suggest that the increased production owing to the use of the HYV's was substantial.

Surjit Sidhu has recently reported the results of a study on wheat in the Punjab of India for the four-year period from 1967/68 to 1970/71.[57] Production, again, was the dependent variable; the independent variables were crop land, capital services, fertilizer/manure, and labor. All independent variables proved to be significant except, in some cases, labor. When production functions were run for HYV and non-HYV farms in 1967/68, it was found that the new varieties used more of all inputs on a per unit of *land* basis; however, "a unit of *output* of new wheat consumes less of all inputs, including land, than old wheat" and this "is of crucial importance as a source of growth."[58]

For the year 1967/68, the "magnitude of the natural upward shift in the wheat production function resulting from the introduction of new wheat" was 22.85 percent.[59] In a subsequent paper, using a somewhat different formulation, Sidhu found an increase in efficiency of 44.79 percent.[60] These two figures form, he feels, the lower and upper limits of the actual change in productivity.[61]

For the other three years of one study, analyses were carried out for HYV's only.[62] The results suggested a downward shift in the production function after 1967/68. Sidhu thought that this drop may have been the result of the weather, the deterioration in seed quality (owing to mixing), and the addition of marginally "inferior lands" but noted that "an assessment of their relative influences seems impossible." The downward shift in the production function, however, was to some extent reversed in 1970/71. Sidhu was not sure whether the downward movement "was a temporary phenomenon or is a long-run technological regression in the production of new wheats."[63]

Sidhu remarks that "during farm visits in 1970 and 1971 Punjab farmers generally complained of defective seed quality after 1967/68. . . . I think mixing of lower quality seed with better seeds occurred at more than one level of the seed distribution channel."[64] If he is right in suggesting that the declining quality of seed may be caused by mixing – and some other recent references from India indicate that he might be – we have another complex and largely unmeasurable variable which should be considered. Forms of "technological regression," however, can be corrected to some extent in national research programs, as Evenson's analysis (cited above) has indicated.

Production functions, though they provide an analytically attractive approach, do have severe data problems unless they are based on farm surveys. And even if they are, there is the problem of extrapolating the results to the national or international level. Is there a way to get around these problems? The index number approach is one possibility.

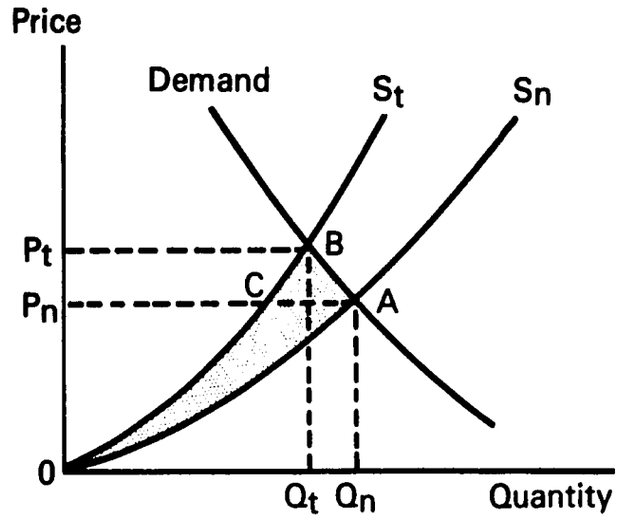


Figure 7-5. Effect of a new technology in shifting supply curves.

Index Number Analysis

New technology usually results in an increase in output for a given set of resources. Through use of the index number approach, it is possible to measure the magnitude not only of this increase but of its value to society. A number of economists have used this approach at the national level.[65] The index number technique can build on some of the results of production function analysis. Although the index number approach does have some limitations, these can be partly avoided by linking this approach with production function analysis.

The general formulation. In economic terms, the introduction of a new technology leads to a shift in the supply curve (graphically shown in Figure 7-5). Curve S_t represents the supply situation with traditional technology. Curve S_n represents the supply situation if the new technology is utilized. With the introduction of the new technology, the quantity of product is increased and the price is reduced. This change results in a gain to society, which is indicated by the shaded area, OAB. (Here I have adopted the simplified depiction of social benefits used by Hayami and Akino in chapter 2.) Since only part of the farming area may utilize the new technology, the actual supply curve would lie somewhere between S_n and S_t.

The usual index number analysis involves a three-stage process, including estimation of (1) gross benefits, (2) research costs, and (3) rate of return over time. Obviously, a full-blown index number study could be rather involved and would demand much data. It also goes beyond the scope of this chapter, which is to evaluate effects on production. Therefore we will focus on step (1), the measurement of gross benefits.

Even the estimation of gross benefits, however, is a rather complex process. The major components and their functional form may be summarized as follows:[66]

$$B = PQK\,(1 + K/2\,E_D)\,(1 - [(1 - E_D)^2\,E_S/(E_D - E_S)])$$

where

B = gross benefits
P = price of the product
Q = quantity of the product
K = shift in supply curve owing to research
E_D = elasticity of product demand
E_S = elasticity of product supply.

The most difficult factor to measure, in turn, is K, since it is hard to separate out the many other factors which may influence productivity. Production function analysis can be very helpful in this process. E_D and E_S may also be difficult to determine over broad areas.

Is it possible, for introductory purposes, to get around some of the data problems by simplifying step (1)? A look at three previous studies provides some help with K, E_D, and E_S.

Several types of estimates of K have been utilized. In his classic study on hybrid corn, Griliches simply assumed, using some industry estimates, that yields were 15 percent higher than for open-pollinated varieties (a shift which he identified as K).[67] A subsequent study, by Ardito Barletta, of the effects of crop research in Mexico made use of three different estimates of K: (1) experiment station results, (2) a weighted average from regression analysis, and (3) a figure obtained by assigning all productivity increases to the new wheat and subtracting the additional costs.[68] Hertford et al. used the results of farm-level experimental trials (see chapter 4). In terms of effects, measures close to the farm level would be most desirable; in terms of measuring potential, experiment station results might be most useful.

How necessary is it that elasticity estimates, E_S and E_D, be included? When Griliches postulated various supply and demand elasticities, he found that "these elasticities have only a second-order effect, and hence different reasonable assumptions about them will affect the results very little."[69] In

a concurrent investigation of the returns to research on a disease-resistant cotton in Brazil, Ayer and Schuh found, in calculating internal rates of return, that the results were changed only a little by different assumptions about the respective price and supply elasticities.[70] In reviewing these three papers, as well as Ardito Barletta's, the Statistics Division of the Ministry of Overseas Development in the United Kingdom summarized calculations which suggested that, when the elasticity of demand is within the range of − 0.5 to − 1.85, changes in the elasticity of supply make little difference (less than 5 percent) in the amount of benefit.[71]

All told, then, these findings suggest that it is possible to be flexible and pragmatic in obtaining estimates of K, and that introductory analyses might leave out estimates of E_S and E_D. Clearly, more precise analyses should include the elasticities.

Contribution of the HYV package. Considering data available for wheat and rice, and the possible simplifications suggested in the previous section, we can readily estimate the gross contribution of the HYV package to production by a sequence of a few simple formulas. Several different values for K, the shift owing to research, will be assumed.

The available and required data are described in the following algebraic notation:

Varieties	*Area*	*Yield*	*Production*
Traditional	A_t	Y_t	Q_t
HYV	A_{hyv}	Y_{hyv}	Q_{hyv}
All varieties	A_T	Y_T	Q_T

K is the equivalent of $\frac{Y_{hyv}}{Y_t}$. Five of the nine variables are known: A_t, A_{hyv}, A_T, Y_T, and Q_T. The variables that need to be calculated are Y_t, Y_{hyv}, Q_t, and Q_{hyv}. Q_t and Q_{hyv} as used here, however, are not simply the production from each type of variety: rather Q_t is the quantity that would be produced if all of the area were planted to traditional varieties, and Q_{hyv} is the additional production owing to the HYV package. Four different levels of K have been postulated: 1.25, 1.50, 1.75, and 2.0.

The estimating process is composed of three steps, each of which utilizes a formula.

(1) Estimated yield of traditional varieties (Y_t)

$$Y_t = \frac{Q_T}{A_t + (A_{hyv} \times K)} .$$

(2) Total production if total area planted to traditional varieties (Q_t)

$$Q_t = Y_t \times A_T.$$

(3) Additional production owing to HYV package (Q_{hyv})

$$Q_{hyv} = Q_T - Q_t.$$

The derivation of formula (1) is

$$Q_T = (A_t \times Y_t) + (A_{hyv} \times Y_{hyv})$$

$$Q_T = (A_t \times Y_t) + (A_{hyv} \times (Y_t \times K))$$

$$Q_T = Y_t(A_t + A_{hyv} \times K)$$

$$Y_t = \frac{Q_T}{A_t + (A_{hyv} \times K)}.$$

This is, as suggested, a fairly simple estimating process. It is also flexible; it can be used at any level for which data are available. The main limitation is, as with the index number approach generally, the derivation and specification of K.

Although a range of assumptions on the value of K has been specified, which one appears to be most realistic? In the past, as noted previously, I have used a rough estimate of 1.25 for the HYV rice package and 2.00 for wheat in Asia. Data from several countries suggest that ratios for wheat range from 1.77 to 3.70 and for rice from 1.10 to 2.58. Sidhu's production function analysis indicates farm-level figures ranging from 1.23 to 1.45 for wheat in the Indian Punjab in 1967/68. Research in Colombia placed the yield advantage in 1971 as 1.46 for the improved wheat varieties and between 1.25 and 1.39 for rice (see chapter 4). Clearly there is a wide variation in the ratios.

One explanation for this range of estimates is that they may describe different things. The HYV package is purposely referred to throughout this chapter. The varieties alone may not have a significant effect on overall production because other elements of the package are needed, particularly increased fertilization. On the other hand, without the improved variety the full utility of the other inputs may not be realized. Although some of these factors may be sorted out at the local level through the use of production function or regression analysis, this is much more difficult to do at the national or international level.

While pure varietal effects have reportedly been sorted out for Colombia, some rather exceptional data were available (see chapter 4). The use of more traditional national data on area planted to varieties and estimated quantity of fertilizer may produce a high degree of intercorrelation. In a study under-

way at the Brookings Institution in 1975, for instance, Roy and Sanderson found such a correlation (r = 0.97) between the area planted to all HYV grains and the estimated use of fertilizer on all grains (including HYV's) in India between 1966/67 and 1973/74. In some cases fertilizer might appear to have a higher correlation with output than the HYV's. If so, this may indicate that the fertilizer figure usually reflects use on both traditional and HYV crops (no one knows how much was actually used on HYV's at the aggregate level) and that the area of the HYV's in the early years in each country is quite small (as shown in Figure 7-1). Hence the HYV figure may be swamped by the fertilizer figure.

Of the various K factors postulated, the most likely for the Asian region as a whole might be 1.25 for rice and 1.50 for wheat. The wheat figure is less than that used a few years ago, partly because of the declines in HYV yields as they are planted more widely within nations (as shown in Figure 7-4 for India) and the fact that some of the newer wheat plantings are in the Near East, where water supplies may be even more limited than they are in South Asia.

When the index number approach is applied to wheat and rice in the non-communist developing nations of Asia for the 1972/73 crop year, the calculations produce the results given in column 2 of Table 7-5. (Column 1, the percentage increase, is simply calculated from some of the original data.) Obviously the results vary considerably, depending on which yield or K factor is utilized. If K factors of 1.25 for rice and 1.50 for wheat are selected as most realistic, the calculations suggest that in 1972/73 the HYV package added 8.7 million metric tons of wheat and 7.7 million metric tons of rice. In terms of the total crop, overall wheat output was increased by 18.3 percent and rice output by 4.9 percent.

These figures may be more meaningful when converted to value terms (column 3 of Table 7-5), though this is a hazardous step since it is difficult to select appropriate prices to use for a broad geographic area. If, to facilitate comparison, one applies the prices used by Evenson ($75/ton for wheat and $100/ton for rice), the gross value of the increased output in 1972/73 is striking: $656 million for wheat and $769 million for rice, or a total of $1.425 billion.

These prices, however, may be on the high side. They are close to international levels and do not reflect the fact that the HYV's, despite improvements in taste and color, still are not exported in quantity and do not bring a premium domestic price.[72] They also do not reflect the effect of increased output on local prices. An increase in output would, of course, result in a decrease in price. The amount of decrease would depend on the price elasticity of demand as well as other factors. Although the price decline reduces the

Table 7-5. Estimated Increase in Wheat and Rice Production in Asia under Different HYV Yield Assumptions, 1972/73 Crop Year[a]

HYV Yield as Multiple of Traditional Yield	Proportion (%)		Quantity (million metric tons)[b]		Value (million dollars)	
	Wheat	Rice	Wheat	Rice	Wheat[c]	Rice[d]
1.25	9.1	4.9	4.2	7.7	314	769
1.50	18.3	9.8	8.7	13.8	656	1,379
1.75	27.4	14.7	11.8	18.4	881	1,841
2.00	36.6	19.6	14.4	23.5	1,080	2,354

Source: HYV area based on background data for Figures 7-1 and 7-2. Other area, yield, and production data derived from statistics compiled by Foreign Agricultural Service. Prices same as those used by Evenson (see Table 7-4, notes c and d).

[a] Excluding People's Republic of China, North Vietnam, Japan, and Israel.

[b] Calculated according to formulas (1), (2), and (3) in text.

[c] At $75 per metric ton.

[d] At $100 per metric ton.

valuation of the added output, it is at the heart of the social benefits arising from the innovation (as shown in Figure 7-5). The introduction of the improved wheats in Mexico, for instance, had a major effect in lowering prices to consumers.[73] In some countries, on the other hand, farm prices are held artificially low, which unduly lowers the valuation of the impact at the national level.

If for these reasons prices are arbitrarily reduced by a third (to $50 per ton for wheat and $67 per ton for rice) to reflect these factors better, the results are still most impressive: an increase of $435 million for wheat and $513 million for rice, or a total gross value of about $950 million. Overall, it is reasonable to suggest that the gross value of the HYV wheat and rice package in 1972/73 was about $1 billion for Asia alone.

Even though the overall output increases – of 18.3 percent for wheat and 4.9 percent for rice – are not great, the areas involved in noncommunist Asia alone are so vast that the total figures are inevitably significant. The monetary values would be even higher if North Vietnam, North Korea, Latin America, and Africa were included. However, if the additional cost of inputs were subtracted from the gross figures, they would of course be lowered.

Comparison of Results

How do the results obtained using index number analyses compare with those obtained by Evenson for 1972/73 using production function analysis (reported in Table 7-4)? The statistical findings, using the same prices, are summarized in the accompanying tabulation. Although the data cannot be

		Increase in Total Production	
Analytical Method	*Crop*	*Percentage*	*Gross Value (million dollars)*
Production function	Wheat	7.4	523
	Rice	9.0	1,359
	Total		1,882
Index number	Wheat	18.3	656
	Rice	4.9	769
	Total		1,425

precisely compared because the specific countries and regions involved differ slightly as between Evenson's analysis and mine, the production function analysis appears to have led to more conservative estimates for wheat, while the index number approach provided a more conservative estimate for rice (Evenson, however, includes Latin America in his computation). The total values were not greatly different, and both estimates easily exceeded $1 billion.

Just as Evenson has done, I could present estimates on production increase and value for the previous years (Table 7-4). But since the yield ratio between HYV's and traditional varieties has changed over time and has generally declined, it might be appropriate to use different yield assumptions for past years. And perhaps the effect of some lower ratios (such as 1.20 for rice) should also be calculated.

The yield advantage may, of course, vary from season to season if there are widespread changes in the weather. It may be significantly reduced where, as has been the case recently, fertilizer supplies are scarce and prices high. On the other hand, lower yields may be offset by higher grain prices in calculating gross returns.

The index number procedure outlined here seems a promising initial measure of the effects of the HYV package. It is simple and flexible. It is reasonable in its data requirements. It can make use of production function analysis. It does not require any arcane skills (or computation equipment).

But these factors may also be its weakness. It is only an introductory process. To be at least reasonably accurate, it requires a more systematic and thorough evaluation of the yield ratios between the HYV package and the traditional practices than we have at present for many areas. And even then, as is typical of the index number approach, it does not separate the precise effect of the HYV's themselves from other factors influencing productivity. Additional production function analyses could be most helpful in resolving these points.

There are several further steps which should be taken to complete the index number analytical package. These include, as noted earlier in this chapter, estimated research costs as well as the calculation of social rates of return. The procedure for the rate of return computations has been well demonstrated by Griliches, Evenson, Ardito Barletta, Ayer and Schuh, Hertford, Ardila, Rocha, and Trujillo, Hayami and Akino, and others cited in this chapter.

This study will not detail these further steps. However, it should be recalled that the total annual investment in wheat and rice research at the international institutes in 1975 was probably no more than $10 million. The counterpart national investment is not known, but if it was approximately the same, the total research investment was still relatively small. It would appear even smaller if a lag effect were added, and the 1972/73 crop value figures linked to the research investment of several years before.[74] In comparison, the increased value of production was somewhere on the order of $1 billion. Thus the returns to investment are probably very high.

In any case, it is important to remember (as suggested earlier), that only part of the benefits are being evaluated. Even when direct effects have been evaluated, the potential influence of the HYV's in communist nations and in developed nations has not been considered.[75] And the expanded base that the improved varieties provide for future improvements has not been valued. Much remains to be measured.

More sophisticated analysis of the direct and indirect effects of the international institutes on crop production must await further study. It will not be an easy task, but the integrated use of production functions and the index number approach can help to provide a more complete evaluation of these effects.

Conclusion

This chapter has outlined the main conceptual and empirical considerations in evaluating the impact of international agricultural research on crop production in developing nations. The process has been applied to high-yielding varieties of wheat and rice.

The task of evaluation is complex. Although the immediate research product can be readily identified, there are many problems involved in linking this product to actual changes in production in the farmers' fields. Moreover, the HYV package may have a number of indirect and qualitative results in addition to the direct and quantitative effects.

This study, after reviewing all these considerations, focused on only one measure: the direct quantitative effect. Changes in area and yield were first examined. This was followed by an analysis of the effect of the HYV's on

yield, using production function and index number techniques. Even this relatively narrow focus encountered a number of analytical difficulties. Some can be solved by using the techniques in combination rather than separately as in the past. Others are more intractable.

Despite these problems, the task is not an impossible one. Crude measures or approximations have been made, and it is certainly possible to make further improvements in evaluation. But to do so will require improved data and analytical techniques. Whether these will be forthcoming will in part depend on the need for improved analysis.

For the moment, the accomplishments of the early centers are well known. They have produced striking technologies whose worth is readily understood. Past studies have shown that investment in research yields high returns. And indeed this preliminary study, while not carried through to the point of calculating an actual cost-benefit ratio, suggests that the returns to international research in wheat and rice must have been very high. Perhaps these findings will be adequate for the near future.

At some point, however, it is likely that more quantitative evidence will be requested. Of all aid recipients, a research organization should be in a good position to provide some measure of its worth. It should be realized that these measures cannot be turned out overnight. Appropriate data must be available. Where data are not available arrangements must be made well in advance for their gathering and assembly. And analytical techniques must be tailored to the job at hand.

Financial resources will be needed to carry out these tasks. Perhaps one or more of the members of the Consultative Group will provide funds for this purpose in the future. Should support become available, the research could be administered in a variety of ways. The newly established International Food Policy Research Institute might play a role in this process (though this institute is not sponsored by the CG at present).

In pursuing a more precise estimate of the effects of technologies, we have recognized several key points. First, the measurement problems, as indicated, are severe. Sponsors need to have some understanding of what can and cannot be readily measured. Second, some research activities might show considerably less quantitative effect than others. Such results might not always be well received, but they ought to be known if resources are to be allocated most effectively.

It should be realized, of course, that quantitative techniques cannot measure everything. Some research programs can be justified on other grounds. And social goals beyond productivity should certainly be considered. Rural equity issues, for example, are becoming increasingly important in the planning process.

The evaluation task, therefore, is broad and challenging. But an enlightened and effective program of international agricultural research requires research on the system itself. It is time to consider a modest but enduring organizational mechanism that can carry out the job.

NOTES

1. The original manuscript of this chapter was titled "Impact of the International Institutes on Crop Production." Following the Airlie House conference, it was revised and published as *Measuring the Green Revolution: The Impact of Research on Wheat and Rice Production*, Foreign Agricultural Economic Report no. 106 (Washington, D.C.: Economic Research Service, USDA, in cooperation with the United States Agency for International Development, 1975). The material presented here is an abridged and slightly revised version of the published bulletin.

2. The origins and dimensions of this work are well reported in E. C. Stakman, Richard Bradfield, and P. C. Mangelsdorf, *Campaigns against Hunger* (Cambridge, Mass.: Belknap Press of Harvard University Press, 1967); and Lennard Bickel, *Facing Starvation: Norman Borlaug and the Fight against Hunger* (New York: Readers Digest Press, 1974).

3. Robert Evenson, "Investment in Agricultural Research: A Survey Paper," prepared for the Consultative Group on International Agricultural Research (October 1973), p. 3.

4. *Ibid.*, p. 3.

5. See Tables 1-1 and 1-2 in this volume.

6. Robert Evenson (with Y. Kislev), "Research and Productivity in Wheat and Maize," *Journal of Political Economy*, 81 (November-December 1973), 1309-1329; Robert Evenson, "International Diffusion of Agrarian Technology," *Journal of Economic History*, 34 (March 1974), 51-73; and Robert Evenson, "The Green Revolution in Recent Development Experience," *American Journal of Agricultural Economics*, 56:2 (May 1974), 387-394. Also, Robert E. Evenson and Yoav Kislev, *Agricultural Research and Productivity* (New Haven: Yale University Press, 1975).

7. Dana G. Dalrymple, *Development and Spread of High-Yielding Varieties of Wheat and Rice in the Less Developed Nations*, Foreign Agricultural Economic Report no. 95 (Washington, D.C.: Economic Research Service, USDA, 1974).

8. A listing of some of the more important works is provided in Dalrymple, *High-Yielding Varieties*, p. 2, footnotes 2 and 3. The following more recent studies might also be added: Keith Griffin, *The Political Economy of Agrarian Change: An Essay on the Green Revolution* (Cambridge, Mass.: Harvard University Press, 1974), and *The Social and Economic Implications of Large-Scale Introduction of New Varieties of Foodgrain* (Geneva: United Nations Research Institute for Social Development, 1974).

9. Evenson places the mean time-lag between expenditures on research and effect on production in the United States at about six and a half years (Evenson, "Investment in Agricultural Research," p. 18).

10. Corn, in many ways, is a more difficult plant to work with. For a discussion of the main problems, see Delbert T. Myren, "The Rockefeller Foundation Program in Corn and Wheat in Mexico," *Subsistence Agriculture and Economic Development*, ed. Clifton R. Wharton, Jr. (Chicago: Aldine, 1969), pp. 438-452.

11. Stakman, Bradfield, and Mangelsdorf, *Campaigns against Hunger*, pp. 5, 12, and 273.

12. *1966-67 Report, CIMMYT*, p. 9.

13. See "CIMMYT's New Headquarters at El Batan," *CIMMYT Report*, 1:1-6 (November-December 1972), 1.

14. From a letter from Robert D. Osler, deputy director general and treasurer, CIMMYT, September 11, 1974.

15. Robert F. Chandler, "IRRI – The First Decade," *Rice, Science and Man*, papers presented at the Tenth Anniversary Celebration of the International Rice Research Institute, Los Baños, April 20 and 21, 1972, pp. 5-7.

16. Unpublished table provided by Randolph Barker, November 29, 1973.

17. For the six centers in 1975, about 46 percent of the proposed core budget would actually go to research. Of the total proposed budget for the six centers in 1975, 27.7 percent would be allocated to wheat and rice. "Draft Integrative Paper," Consultative Group on International Agricultural Research (July 24, 1974), p. 4, annex A.

18. Computed from data provided by Nicolas Ardito Barletta, "Costs and Social Benefits of Agricultural Research in Mexico," Ph.D. dissertation (Chicago: University of Chicago, 1971), p. 74.

19. Lowell S. Hardin and Norman R. Collins, "International Agricultural Research: Organizing Themes and Issues," *Agricultural Administration*, 1 (1974), 14.

20. See particularly chapters 12, 13, 14, and 15 in this volume.

21. Surjit Sidhu, "Economics of Technical Change in Wheat Production in the Indian Punjab," *American Journal of Agricultural Economics*, 56 (May 1974), 217-226. On the profitability of HYV rice in six Asian nations, see Randolph Barker, "Changes in Rice Farming in Selected Areas of Asia: Some Preliminary Observations," mimeographed (Los Baños: International Rice Research Institute, February 15, 1973), p. 7.

22. For further details on the matters discussed here, see Dalrymple, *High-Yielding Varieties*, pp. 9-20.

23. Stakman, Bradfield, and Mangelsdorf, *Campaigns against Hunger*, pp. 74-88.

24. *CIMMYT Review, 1974*, p. 7. (The three types are stem rust, leaf rust, and stripe rust.)

25. For more detailed discussion of maintenance research in the United States context, see Peterson and Fitzharris, chapter 3 in this volume.

26. For further and more sophisticated discussion of this matter, see Richard E. Just, "Risk Aversion under Profit Maximazation," *American Journal of Agricultural Economics*, 57 (May 1975), 347-352.

27. Dana G. Dalrymple, "The Green Revolution and Protein Levels in Grain," Unpublished manuscript, USDA, Economic Research Service, Foreign Development Division (Washington, D.C., May 5, 1972). See, for example, *IRRI Research Highlights for 1973*, pp. 22-24.

28. Gelia T. Castillo, "Diversity in Unity: The Social Components of Changes in Rice Farming in Asian Villages," *Changes in Rice Farming in Selected Areas of Asia* (Los Baños: International Rice Research Institute, 1975), p. 349.

29. See Dana G. Dalrymple, *Survey of Multiple Cropping in Less Developed Nations*, Foreign Agricultural Economic Report no. 91 (Washington, D.C.: USDA, 1971).

30. Ian R. Wills, "Projections of Effects of Modern Inputs on Agricultural Income and Employment in a Community Development Block, Uttar Pradesh, India," *American Journal of Agricultural Economics*, 54 (August 1972), 457-458.

31. *CIMMYT Review, 1974*, p. 7.

32. See Dalrymple, *High-Yielding Varieties*, pp. 17-21.

33. See Robert Evenson, "Consequences of the Green Revolution," Department of

Economics, mimeographed (New Haven: Yale University, July 1974), p. 387; Dalrymple, *High-Yielding Varieties*, pp. 9-20.

34. *IRRI Research Highlights for 1973*, p. 46.

35. Dalrymple, *High-Yielding Varieties*, pp. 71, 72.

36. *IRRI Research Highlights for 1973*, p. 45. The data may overstate the importance of insects and diseases in the Philippines as a whole (letter from Robert W. Herdt, agricultural economist, IRRI, September 30, 1974).

37. William Jones (of World Bank) and I have reviewed these categories in greater detail in "Evaluating the 'Green Revolution,'" processed draft, USAID, Bureau for Program Policy and Coordination (Washington, D.C., June 18, 1973), pp. 33-37.

38. *IRRI Research Highlights for 1973*, p. 45.

39. A summary of some of these studies and factors is provided in Dalrymple and Jones, "Evaluating the 'Green Revolution,'" pp. 37-39; and Dana G. Dalrymple, "The Green Revolution: Past and Prospects," processed draft, USAID, Bureau for Program Policy and Coordination (Washington, D.C., July 22, 1974), pp. 13-16, 45-47.

40. For a summary of available information, see Dalrymple, *High-Yielding Varieties*, pp. 73-77.

41. Based on review of statistics compiled by John Parker, Economic Research Service, USDA.

42. Carl C. Malone, *Indian Agriculture: Progress in Production and Equity* (New Delhi: Ford Foundation, 1974), p. 99, Table 20.

43. Sidhu, "Technical Change," p. 221.

44. Sheldon K. Tsu, *High-Yielding Varieties of Wheat in Developing Nations*, Economic Research Service-Foreign 322 (Washington, D.C.: USDA, 1971).

45. Based on statistics compiled by John Parker, Economic Research Service, USDA, May 20, 1974.

46. Mahar Mangahas and Aida R. Librero, "The High-Yield Varieties of Rice in the Philippines: A Perspective," Discussion Paper no. 73-11, School of Economics, Institute of Economic Development and Research (Los Baños: University of the Philippines, June 15, 1973), p. 23.

47. Calculated from Teresa Anden and Randolph Barker, "Changes in Rice Farming in Selected Areas of Asia," mimeographed (Los Baños: International Rice Research Institute, December 1, 1973), Table 8.

48. L. J. Atkinson and David Kunkel, "HYV in the Philippines: Progress of the Seed Fertilizer Revolution," unpublished manuscript, USDA Economic Research Service, Foreign Development Division (Washington, D.C., December 10, 1974), Appendix Table 1. Other computational variations are presented in the appendix and discussed in the text, pp. 5-7.

49. Further detail on the latter point is provided in Dalrymple, *High-Yielding Varieties*, pp. 9-15.

50. These approaches are introduced and described by Willis L. Peterson, "Return to Poultry Research in the United States," *Journal of Farm Economics*, 49 (August 1967), 653-669, and Per Pinstrup-Andersen, "Toward a Workable Management Tool for Research Allocation in Applied Agricultural Research in Developing Countries," International Center for Tropical Agriculture, mimeographed (Palmira, Colombia, June 1974), pp. 3-6.

51. Evenson, "Green Revolution in Recent Development Experience," p. 388.

52. As of early 1975, these indexes were being used by Shyamal Roy and Fred

Sanderson in a study at the Brookings Institution. The indexes for 1951/52 to 1968/69 and the methodology used in their calculation are provided in R. W. Cummings, Jr., and S. K. Ray, "1968-69 Foodgrain Production: Relative Contribution of Weather and New Technology," *Economic and Political Weekly* (New Delhi, March 29, 1969).

53. Evenson, "Green Revolution in Recent Development Experience," pp. 387-394. Also see chapter 9 in this volume.

54. Evenson, "Green Revolution in Recent Development Experience," p. 393.

55. Evenson, "Consequences of the Green Revolution," p. 13.

56. The first set was reported in Evenson, "Green Revolution in Recent Development Experience," p. 393. The second set was reported in Evenson, "Consequences of the Green Revolution," p. 14, and in the preliminary version of his Airlie House paper; these data were also summarized in Dalrymple, *Measuring the Green Revolution*, p. 31, Table 6. The main difference between the second stage and the third stage in Table 7-4 was the use of geometric rather than arithmetic means and the use of somewhat more accurate production costs.

57. Sidhu, "Technical Change," pp. 217-226.

58. Letter from Surjit Sidhu, University of Dar es Salaam, Tanzania, October 2, 1974.

59. Sidhu, "Technical Change," p. 219.

60. Surjit Sidhu, "Relative Efficiency in Wheat Production in the Indian Punjab," *American Economic Review*, 64 (September 1974), 743-744.

61. Letter from Surjit Sidhu, University of Dar es Salaam, Tanzania, November 12, 1974.

62. The comparative analysis of old versus new varieties was carried out only for 1967/68 "because during the subsequent years, the number of farms growing old wheat and the area planted to it were substantially reduced." Sidhu, "Technical Change," p. 217.

63. *Ibid*,. pp. 222-223.

64. *Ibid*., p. 223, n. 11. Some other references to seed quality are summarized in Dalrymple, *High-Yielding Varieties*, pp. 32-34.

65. The seminal application was by Zvi Griliches in his study on hybrid corn. This work was reported in several journals; here I refer to "Research Costs and Social Returns: Hybrid Corn and Related Innovations," *Journal of Political Economy*, 66 (October 1958), 418-431. Major studies of the LDC's have included Nicolas Ardito Barletta, "Agricultural Research in Mexico"; Harry W. Ayer and G. Edward Schuh, "Social Rates of Return and Other Aspects of Agricultural Research: The Case of Cotton Research in São Paulo, Brazil," *American Journal of Agricultural Economics*, 54 (November 1972), 557-569; chapter 4 in this volume; chapter 2 in this volume.

66. This formulation is taken from Pinstrup-Andersen, "Research Allocation," pp. 3-6.

67. Griliches, "Research Costs and Social Returns," pp. 419-431.

68. Ardito Barletta, "Agricultural Research in Mexico," pp. 79-89.

69. Griliches, "Research Costs and Social Returns," pp. 419-431.

70. Ayer and Schuh, "Social Rates of Return," p. 561.

71. "A Note on the Use of Commodity-Based Studies in Estimating the Pay Off to Investment in Research," Ministry of Overseas Development, Statistics Division, London, September 1974.

72. See, for example, Anden and Barker, "Changes in Rice Farming," pp. 6-7.

73. This matter is discussed by Jones in Dalrymple and Jones, "Evaluating the 'Green Revolution,'" pp. 15-31. Evaluation of returns to research must give considerably more attention to the price effect.

74. Recall, from n. 9, Evenson's use of a lag figure of six and a half years in the United States. The interval would probably be even greater in the LDC's.

75. A study of the influence of the HYV's in Israel, for instance, was recently completed. It suggested that the influence of the first imports was minimal but that they did become significant when crossed with local varieties. See Yoav Kislev and Michael Hoffman, "Research and Productivity of Wheat in Israel," Center for Agricultural Economic Research (Rehovot: Hebrew University, February 1975).

8

Cycles in Research Productivity in Sugarcane, Wheat, and Rice

Robert E. Evenson

The recent green revolution in wheat and rice production is not unique in the history of the improvement of agricultural productivity. We can identify a number of similar episodes in which a distinct cycle of productivity gains has occurred, attended by an associated pattern of interregional and international diffusion of the primary technology. The improvement of winter wheat in the 1920s, of European alfalfa varieties in the 1930s and 1940s, and of spring wheats and barley varieties in the 1940s and 1950s in the United States are cases in point. This chapter discusses major productivity sequences in sugarcane. It also briefly considers rice and wheat production and attempts to identify some of the elements common to the development of research in all three crops.

In the first section the stylized cycle of productivity development is discussed. The sections to follow provide a historical treatment of the sugarcane productivity cycle and a brief history of the rice and wheat cycles. An attempt is then made to set forth at least a partial theoretical framework capable of providing an explanation for the cyclical phenomenon and the associated diffusion pattern.

The Stylized Cycle

The salient features of the cycle are as follows.

At first, a state of relative or "quasi"-technology equilibrium exists. It may

be based on strictly traditional technology or on a relatively stationary or stagnant phase in the improvement of technology. (Technology can refer to crop varieties, agronomic techniques, mechanical implements, or other aspects of production. Similarly, commodity quality characteristics can be considered part of technology.)

New technology (or a set of closely related technologies) which has a high degree of superiority over the initial technology is then discovered. This discovery may itself be described as having occurred over a long interval, but the final development of the technology occurs in a short period of time.

In the next stage, improvements to the new technology are made, but at a diminishing rate over time. Even with increased research, the incremental rate of improvement declines over time and approaches zero (in some cases it may become negative, as crop varieties, for example, become susceptible to insect and disease problems).

Whereas in the initial quasi equilibrium a wide range of technologies are utilized by producers who confront varying environmental and economic conditions, the discovery of a significant new technology leads, in the next stage of our cycle, to diffusion of that technology directly from the region of its origin to other, similar regions.

A considerable amount of screening and testing, sometimes necessitating sophisticated equipment and skills, is then required to enable efficient diffusion of the new technology. Even with perfect information, however, the direct diffusion of technology is ultimately limited by environmental and economic conditions.

In the next stage the new technology begins to provide incentives for indirect diffusion through "adaptive" research. This can be considered to be a diffusion of technical and engineering *knowledge* as opposed to the diffusion of technology. Adaptive research extends the geographical impact of the technology by tailoring it to specific environmental conditions. This research, like the originating research program, is subject to diminishing returns.

Finally, a new quasi equilibrium with characteristics similar to the original equilibrium is reached. Numerous forms of the basic technology are in use, and the initiating technology improvement occurs in all regions. This stylized cycle does not necessarily hold for all types of technology improvement sequences. In fact, as will be noted in a later section, efficient technology improvement should generally be a relatively smooth process through time. Much of the realized productivity gain from technology improvements in modern agriculture does not exhibit marked cyclical activity. Part of this is more apparent than real, however, because we tend to observe aggregate blocks of technology. Aggregation of cyclical series can easily mask the cycles.

In a later section, we will develop a rationale for expecting greater cyclical

activity in commodities where production is based on more primitive or traditional technology and in regions where relatively little research capability exists.

Sugarcane Varietal Improvement[1]

The several stages in the stylized productivity cycle can be clearly discerned from the history of sugarcane development.

The Initial Quasi Equilibrium

From the sixth century to the seventeenth century a single variety of sugarcane, the "Creole" (a hybrid with sterile flowers and thus incapable of sexual reproduction), was produced throughout the world. During the seventeenth century a second variety, the "Bourbon" or "Otaheite" cane, was discovered on the island of Tahiti in the Pacific and later introduced to all cane-growing areas of the world. It proved to be superior to the Creole variety and eventually replaced it as the dominant cane in most producing countries. It is of interest to note that it was not introduced to the British West Indies, a major cane-producing area, until 1785-86, more than a hundred years after it was first known to have been commercially produced in Madagascar and on Bourbon (or Réunion) Island. Produced under a variety of names (Lahania, Vellai, etc.), it dominated world production until it became subject to disease in 1840 in Mauritius, in 1860 in Puerto Rico, in the 1890s in the British West Indies, and in the early twentieth century in Hawaii.

A third major set of wild canes, the "Batavian" canes, were discovered in Java about 1782. These canes were eventually produced in many countries (for example, as the "Crystalina" in Cuba, "Rose Bamboo" in Hawaii, and the "Transparent" canes in the British West Indies) but were not always superior to the Bourbon cane. After the disease epidemics in the Bourbon cane, the Batavian varieties became dominant. However, they were later subject to the Sereh disease in many parts of the world. Other wild varieties were discovered in the late 1800s, including the "Tanas" from New Hebrides, "Badila" from New Guinea, and "Uba," probably from India. Badila and Uba became important varieties because of their resistance to the cane diseases which became increasingly prevalent from 1890 to 1925.[2]

The First Major Cycle

The original sugarcane varieties undoubtedly arose as seedlings from rare cases of natural sexual reproduction. Several reports of seedling growth were made after 1858,[3] but it was not until the 1887-88 cane-growing season – when the fertility of the cane plant was firmly established – that a basis for

the deliberate use of seedlings for producing new varieties existed. In the early part of that crop year Soltwedel in the Proefstatien Oost Java (POJ, the experiment station in Java which later became the world's leading producer of important varieties) demonstrated that the sugarcane plant could produce seedlings. Later that same year Harrison and Bovell in the newly established experiment station in Barbados, British West Indies, independently made the same discovery. The researchers at both stations recognized that each individual seedling could be grown and allowed to reproduce asexually, thus creating an entirely new variety having the same genetic characteristics as the seedling.

The inducement of flowering in the cane plant depends on temperature and light control. Thus, the production of seedlings was difficult. Only a few experiment stations, including the two pioneer stations in Barbados and Java, were able to establish breeding programs before 1900. The stations in Barbados, Java, and British Guiana (where Harrison made his home shortly after his discovery of cane fertility in Barbados) had produced new varieties which were of commercial importance by that date. The stations in Hawaii, Mauritius, and Réunion produced commercial varieties shortly thereafter.[4] The Indian station at Coimbatore, which later assumed major importance, did not release its first variety until 1912.

These early "noble" sugarcane varieties were all members of the eighty-chromosome species *Saccharum officinarum*. Breeding methods were relatively simple, although as breeders gained experience advances were made. A certain amount of adaptive research appears to have been undertaken during this first cycle, as a number of new experiment stations initiated breeding programs. Bovell, for one, developed in 1900 a breeding program of "selfing" which, by inbreeding, identified the characteristics of progeny of specific varieties and thereby determined their value as breeding stock.[5] By 1910 or so most of the important varieties of this cycle had been developed.

This first cycle resulted in considerable international diffusion, for many countries introduced the noble varieties which initially outyielded the native varieties. However, in a great many cases (e.g., South Africa), this initial superiority was not maintained. A number of serious disease epidemics among the new varieties eliminated their advantage over the disease-resistant native varieties, and considerable retrenchment of the initial diffusion occurred.

The Second Cycle: Interspecific Hybridization

Cane breeding achieved a major advance with the introduction of additional cane species to the breeding program. The term *nobilization* was used to describe the breeding work in Java which sought to improve the wild species of cane (hardy and disease-resistant, but otherwise inferior) by succes-

Table 8-1. Varietal Production of Various Sugarcane Experiment Stations, 1940-64 (in million metric tons)

Experiment Station	Varieties in Production		Variety Parents		Variety Grandparents	
	Production[a]	Rank	Production[a]	Rank	Production[a]	Rank
Coimbatore, India	64.7	1	75.4	2	53.8	3
Java (POJ)	63.4	2	102.3	1	113.6	1
Hawaii	24.9	3	18.1	4	16.8	4
Cuba	20.4	4				
Barbados, B.W.I.	10.8	5	18.8	3	59.4	2
Canal Point, Florida	10.3	6	4.5	6	4.2	7
Queensland	9.1	7	3.3	7		
South Africa	7.3	8	0.3	10	0.3	9
Taiwan	4.2	9				
Mauritius	4.2	10	1.7	9	6.0	6
Brazil	3.9	11	1.8	8	1.8	8
British Honduras	3.9	12				
Puerto Rico	3.8	13				
Peru	2.2	14				
British Guiana	0.2	15	8.5	5	12.2	5

Source: *Yearbook of Agriculture*, USDA (Washington, D.C.: Government Printing Office, 1936), pp. 561-624; *Proceedings of the Twelfth Congress*, International Society of Sugarcane Technologists, New York, 1967, pp. 844-854; *Agricultural Statistics*, USDA (Washington, D.C.: Government Printing Office), various issues.

[a] Total production of 96 percent sugar, 1940-64 (million of tons).

sive crossing and backcrossing with the noble canes. The breeders in Java introduced the species *Saccharum spontaneum* (chiefly a wild variety, "Kassoer") to their breeding program, obtaining important results by 1920. In 1921 the variety POJ 2878 was produced by this program. It proved to be both disease-resistant and high-yielding. More than 50,000 acres were planted to this variety in Java alone by 1926. By 1929, 400,000 acres were in production, with an estimated 30 percent yield increase owing to this single variety. It later was planted in every producing country in the world.

The Coimbatore Experiment Station in India developed a series of trihybrid canes (the CO varieties) by using the noble *S. officinarum* and the vigorous *S. spontaneum* species and introducing a third species, *S. barberi*. The *S. barberi* canes were local varieties which possessed characteristics that afforded adaptability of the resultant new varieties to environmental and economic conditions. The CO and POJ varieties were eventually diffused to almost every producing country (see Table 8-1).

The expansion of the genetic base for varietal discovery was a very im-

Table 8-2. Percentage of Total Sugarcane Acreage Planted to Varieties Developed by Experiment Stations of Selected Countries, 1930-65

Region	1930	1940	1945	1950	1955	1960	1965
Australia	20	20	33	54	83	85	85
Hawaii	50	65	82	100	100	100	100
South Africa. . .	0	0	0	3	49	78	n.a.
Taiwan	0	32	46	56	10	4	42
Puerto Rico . . .	0	9	12	10	3	35	50
Mauritius.	0	8	53	98	93	78	n.a.
Louisiana.	0	23	52	77	65	65	n.a.

Source: *Annual Report*, Bureau of Sugar Experiment Stations, Queensland, Australia, various issues, 1928-64; *Proceedings of the Twelfth Congress*, International Society of Sugarcane Technologists, New York, 1967, pp. 867, 1041; *Culture of Sugar Cane for Sugar Production in Louisiana*, USDA Agricultural Handbook 262, Washington, D.C., 1964.

portant feature of this second cycle. It not only resulted in slower rates of diminution, or "exhaustion," of the technology potential in each country, but it broadened the scope for direct varietal diffusion. In addition, it formed the basis for effective adaptive research programs utilizing local native species. The second cycle thus developed into a full cycle in the context of the stylized cycle.

During the 1920s and 1930s virtually all sugarcane-producing countries established experiment stations as they recognized the potential gains to be had from (1) the varietal screening activity to facilitate direct transfer and (2) adaptive breeding programs. These "second cycle" research programs generally began to release adapted varieties in the late 1930s, but their major contributions were seen in the varietal releases of the 1940s and the early 1950s. Of course, the first cycle stations continued in the second cycle to be the major technology discovery institutions.

Interestingly, almost all the second cycle experiment stations were successful in coming up with adapted varieties even though a large number of improved varieties in the international market were readily available. This near unanimous success is partly reflected in Table 8-2, which shows the increasing percentage of "home-grown" varieties planted in several countries. Of the countries included in the table, South Africa, Taiwan, and Puerto Rico can be roughly categorized as second cycle stations. The remainder were active in the first cycle.

The Third Cycle: The Modern Experiment Station

In a somewhat crude sense, it is possible to identify a third cycle associated with the development of modern research programs based on sophisticated

scientific knowledge. These systems are undertaking work in genetics, physiology, and related fields as well as in plant breeding and agronomy. Improved experimental design and screening methods are utilized. These research systems are adapting their technology discovery effort not only to environmental and changing economic conditions (for example, development of machine harvesting technology – a major adaptive economic response) but to advances in scientific knowledge as well.

Given the relatively long lag between the conduct of research and realized productivity gains, this third cycle has been important only in the 1960s and 1970s. It represents an important institutional development, however, which will be touched upon later.

International Diffusion and Yield Patterns

As noted earlier, the direct diffusion of the first cycle varieties, while extensive, was limited by the susceptibility of the noble varieties to disease. The second cycle was characterized by very extensive international varietal diffusion. A rough picture of the extent of this diffusion can be obtained from Table 8-1, which summarizes international production of sugar (from cane) for the period 1940-64 in terms of the experiment stations which developed the varieties grown. In addition, a computation of the origin of parent and grandparent varieties by experiment station is reported. The production figures show that the experiment station in Coimbatore, India, had produced varieties which accounted for almost 28 percent of the world's sugarcane production even though India accounted for only 8 percent of the world sugar production during the period.

Indonesia (Java) also produced varieties accounting for roughly 28 percent of the world's sugarcane production while producing only 2 percent of the world's sugar from cane. Cuba, on the other hand, produced 22 percent of the world's cane sugar but Cuban varieties accounted for only 8½ percent of the world's production.

The bulk of the varieties in production during this period were second cycle varieties. Some first cycle varieties were still in production in a few countries, however. If data were available for a later period, say the early 1970s, a number of third cycle varieties would be present, but most production in the world in this period would be the result of adapted second cycle varieties.

The table provides some evidence for the pattern of adaptive research. The dominant parental and grandparental role of the POJ varieties from Java identifies these as key originator varieties. Likewise, the Barbados grandparent varieties were important source material for adaptation.

Table 8-3 presents historical production and yield data for sugarcane for major producing countries. These data, it should be noted, are subject to

Table 8-3. National Sugarcane Yield and Production Averages for Selected Five-Year Periods

Area	Production[a]	Yield[b]							
		1910-14	1923-24	1928-32	1938-42	1948-52	1958-62	1963-67	1968-72
Brazil	5,329	n.a.	n.a.	n.a.	17.1	17.4	18.8	19.8	21.0
Cuba	4,950	14.5	19.3	18.6	17.2	17.0	17.0	16.2	21.0
India	4,515	11.3	11.0	12.4	11.5	13.1	15.3	20.8	21.7
Mexico	2,319	n.a.	30.2	20.5	22.4	23.1	26.4	27.0	28.6
Australia	1,643	17.3	16.8	16.9	20.3	23.6	27.5	36.2	36.2
Philippines	1,584	n.a.	n.a.	20.4	22.6	20.3	26.7	19.3	20.3
Argentina	1,422	11.6	13.2	13.6	13.4	14.9	17.0	23.0	21.7
U.S. (Hawaii)	1,275	40.7	43.3	60.1	65.1	76.4	90.0	98.7	97.0
U.S. (Louisiana, Florida)	1,104	15.8	9.4	15.0	19.3	19.5	24.5	25.3	26.0
Taiwan	1,100	11.8	16.1	29.3	n.a.	27.3	33.7	38.6	37.2
South Africa	1,002	n.a.	8.8	20.5	26.3	25.1	35.3	35.8	37.5
Puerto Rico	897	n.a.	16.6	25.3	32.4	29.8	30.4	30.6	31.5
Peru	882	22.4	24.3	40.5	52.6	60.0	70.4	64.2	79.6
Indonesia (Java)	854	41.2	46.5	56.4	61.5	40.0	49.5	39.1	34.5
British West Indies	801	n.a.	9.6	24.0	17 6	38.1	39.4	36.4	33.7
Dominican Republic	800	n.a.	n.a.	n.a.	19.0	n.a.	19.5	22.5	27.5
Mauritius	732	15.6	14.5	15.2	19.8	n.a.	24.6	24.0	30.6
Egypt	465	18.8	n.a.	35.0	n.a.	32.8	42.6	40.0	41.9
Mean yields		20.09	19.97	26.48	25.17	29.90	33.81	34.31	35.97
Coefficient of variation		.503	.763	.532	.679	.475	.562	.548	.550
Change in mean yield[c]		n.a.	1.35	6.34	.03	3.88	5.38	.50	1.66

Source: *Yearbook of Agriculture*, 1925-35, *Agricultural Statistics*, 1936-72, and *International Sugar Situation*, 1904, USDA, Washington; *Production Yearbook*, 1948-72, FAO, Rome; *Annual Report*, 1900-64, Bureau of Sugar Experiment Stations, Queensland, Australia; *South African Sugar Yearbook*, South African Sugar Journal, Durban, 1935, 1948-49, 1961-62.

[a] Average annual production in thousands of short tons of 96-degree sugar in 1963-67.

[b] In short tons of cane per acre per year.

[c] Based on common observations.

some error but, on the whole, they serve to identify major trends. The mean yield data and the coefficient of variation in yields provide a crude measure of the overall cyclical effects. The 1910-14 period is early in the first cycle. The noble varieties were beginning to be diffused from the originating countries. By 1923-24, the first cycle diffusion was well under way and by 1928-32 it had been completed. Note that the coefficient of variation of yields reflects the unequal rate of diffusion. It increases in the mid-cycle (1923-24) period and decreases at the end of the cycle.

The second cycle is actually divided into two phases. The 1938-42 period is roughly the mid-period of the direct diffusion of the second cycle varieties. By 1948-52 this direct diffusion was completed, but the adapted varieties were now beginning to increase production. By 1958-62, the adapted second cycle varieties had increased yields substantially. The third cycle is crudely reflected in the 1968-72 data which show increasing yields and yield variability.

This simple comparison of yields and yield variability over time is not intended to be a thorough analysis of productivity change. Yields are not ideal indexes of productivity, and the variability in yield levels internationally is obviously related to many factors besides the underlying technology diffusion pattern. The main purpose of these comparisons is to note the broad consistency of these data with the cycle interpretation of the historical varietal data.

The Role of the Experiment Station in Variety Development and Diffusion

The role of the sugarcane experiment station was not confined to the production of new varieties. It served in an important way to facilitate the international diffusion of the first and second cycle varieties. Experiment stations for sugarcane research were established in many countries where public support of general agricultural research was limited or nonexistent. The support for many stations came from organizations of private growers. The private growers were aware of the changes in the comparative advantage that new varieties (and related technology) would give them in the international market. They were also aware of the comparative disadvantage resulting from improved yields and lowered costs of production which other countries might realize. Although some first cycle cane breeding was undertaken by large private plantations in Hawaii, Cuba, and Java, it soon became clear that it was not profitable to make large investments in private effort because the plantation was unable to capture more than a small fraction of the benefits. It is also true, of course, that sugar producers will not capture the full benefits from improved varieties. In fact, most benefits are likely to be realized by

consumers. A recognition of this has resulted in general public support for modern cane experiment stations.

The initial establishment of experiment stations was clearly based on the colonial interests of the British, Dutch, French, and Portuguese. They well understood the principle that Hertford and Schmitz have elaborated in chapter 6: that the gains from improved technology tend to be passed on to the consumers of the product. It was very much in their interests to support research stations in the sugar-producing colonies. From their point of view, these investments paid off quite handsomely.

The South African case is instructive in this regard. The sugar industry in South Africa was established in 1849. Before 1880 several wild varieties imported from Java, Mauritius, and India were cultivated. A wild variety, Uba, was introduced in 1883 and proved to be more disease-resistant than the other varieties. For a period of fifty years it was the only important variety grown.[6]

During this fifty-year period some experimentation was carried on by planters to find new varieties. A number of potentially important first cycle (and some second cycle) varieties actually existed and were widely planted in many countries. However, it was not until an experiment station, financed by the growers, was established at Mount Edgecumbe in 1925 that varieties from Java and India were introduced to the South African growers. The accomplishments of this station, from 1925 until 1945, were confined to the introduction of new disease-resistant second cycle varieties, mostly from Java and India.

The portion of the South African crop composed of these varieties rose from 3.3 percent in 1933-34 to 19.5 percent in 1942-43. An analysis of yield increases based on a direct comparison of Uba and non-Uba yields indicated that by 1945 the new varieties outyielded the Uba variety by a factor of 27 percent. The South Africa station released the first variety from its own breeding program in 1947 (N:Co:310). This variety was the result of cooperative effort with the Indian Experiment Station at Coimbatore. The actual crossing was completed in the Indian station, and the South African station conducted the growing and selection processes. The experiment stations in Australia (at Queensland), Taiwan, Mauritius, Puerto Rico, and several other countries were also instrumental in the testing and introduction of first and second cycle varieties from other countries into their local economies.[7]

It is possible then to distinguish between several different products of the experiment station systems. The discovery and development of the first cycle varieties were of immense value, as was the development of the basic second cycle varieties. In addition, however, the experiment station provided screening and other vital assistance to the basic diffusion of second cycle varieties.

Table 8-4. Variety Adoption Analysis: Twenty-one Diffused Varieties of Sugarcane[a]

Regression Number	Dependent Variable	Peak percentage (K)	Research (R/P)	Constant	R^2
1	Years from introduction to peak (N)	.127 (5.95)	− 124.0 (5.27)	7.20	.73
2	Average adoption rate (K/N)		112.6 (4.13)	1.80	.48

Source: The *1936 Yearbook of Agriculture* (U.S. Department of Agriculture, 1936) reports the results of a survey of sugarcane research stations throughout the world. The research variable was constructed from these data and from other information on the dates of establishment of stations in Queensland, Puerto Rico, and South Africa.

The countries and states to which varieties were diffused, the names of varieties, and the dates of their introduction are as follows: Puerto Rico: D109 (1910), D625 (1913), BH10 (1920), SC 12/4 (1922), POJ 2878 (1930), M336 (1944); Queensland, Australia: POJ 2878 (1933), Co. 290 (1937), CP 29/116 (1945); South Africa: Co. 231 (1934), Co. 331 (1938), Co. 310 (1936); Louisiana: POJ 2878 (1925), POJ 213 (1927), Co. 281 (1930), Co. 290 (1933); Cuba: POJ 2878 (1932), Co. 213 (1932), Co. 281 (1932); British Guiana: POJ 2878 (1934); Jamaica: POJ 2878 (1932).

Abbreviations:

N = Number of years from introduction to peak percentage (sample mean 9.05).

K = Peak percentage of variety (sample mean 34).

R = Number of senior researchers in recipient country (sample mean 5.92).

P = Production of sugar (at time of introduction) in thousand tons of crude sugar (sample mean 997).

[a] t values are given in parentheses.

At a somewhat later point, many stations contributed through adaptive research, and in the modern setting experiment stations are discovering new, third cycle type technology.

Some evidence is available regarding the contribution of research to a number of these dimensions. It should be interpreted in light of the underlying complexity of the technology discovery process. For example, estimated rates of research productivity should be considered as short-run rates and cannot be expected to remain constant. And, of course, the apparent value of research will depend on the stage of the cycle.

Consider first some evidence regarding the role of research stations in speeding up the adoption of second cycle varieties. Table 8-4 presents a simple regression analysis of the speed of adoption of twenty-one first and second cycle varieties in seven different countries. The analysis shows that the rate of adoption after initial introduction (defined as the date when 1 percent

of the country's acreage was planted to the variety) is speeded up by research activity in the recipient countries.

Regression 1 indicates that when the peak adoption percentage is held constant, the number of years required to reach the peak percentage decreases in proportion to the research undertaken. In elasticity terms, it indicates that a 10 percent increase in research shortens time for adoption by 3 percent.

Regression 2 measures the relationship between the average adoption rate per year and research activity per unit of output. It is shown later that the economic value of speeding up adoption, even by a small percentage, is significant; this, however, requires an estimate of the relationship between the rate of introduction of new varieties and sugarcane production.

Yield levels by variety are reported annually for South Africa. This allows a direct comparison between yields of the old varieties and of the new set of varieties. Additional data on fertilizer use and on the age structure of the varieties are also available. The latter information is particularly important for this type of comparison. Cane is typically "ratooned" for several years. The first crop in a life cycle is produced from planted cane. Subsequent crops in the life cycles are simple regrowths of the same plants after cutting and are referred to as ratoon crops. Depending on climate and other factors, yields decline with each ratoon crop. In South Africa, for example, the index of relative yields by ratoon crops is as follows: plant, 109.8; one year, 108.5; two years, 100.5; three years, 91.0; four years, 86.7; and five years, 82.3. It eventually becomes profitable to plow the fields and replant the cane.

Consequently, simple comparisons of yields by variety, uncorrected for the age differences in the new and old varieties, are misleading. The actual yields in South Africa of the varieties introduced during the 1930s were 43 percent higher than the yield levels of the native variety Uba. This calculation was based on data for the 1935-39 period when both types of varieties were grown. The correction for the age distribution of the canes reduces this to a 27 percent advantage for the second cycle varieties. A comparable set of variety-yield-ratoon data for the period of 1954-57 allowed a comparison to be made of the advantage of adapted second cyle varieties over the original second cycle varieties. This was calculated to be 28 percent. (Note that all computations were made on the basis of sucrose yield, not cane yields. In fact, much of the advantage of the second cycle varieties over the first cycle varieties was in sucrose content.)

Varietal data reported for other countries are not as detailed as they are for South Africa, although data on variety composition of production are generally available. An analysis of yield changes in several countries with regard to the adoption periods of second cycle and adapted second cycle varieties is shown in Table 8-5.

Table 8-5. Yield-Variety Relationship Estimates[a]

Regression Number	Region	Period	Variety "turn-over" (DV)	Changes in Fertil-izers (DF)	Changes in Rain-fall (DR)	Constant	R^2
			Original Second Cycle Varieties				
1	Caribbean Islands	1935-46	.188 (2.21)	4.66 (2.07)	.156 (1.90)	− 3.17	.22
2	Australia	1936-45	.777 (2.72)	n.a.	n.a.	− 4.58	.56
3	South Africa	1933-44	.163 (1.99)	n.a.	.183 (1.87)		.15
			Adapted Second Cycle Varieties				
4	Australia	1945-58	.465 (1.94)	n.a.	n.a.	− 4.83	.24
5	South Africa	1945-62	.222 (1.90)	n.a.	n.a.	− 1.69	.18
6	India (Andhra Pradesh)	1954-61	.345 (1.43)	n.a.	n.a.	− .758	.33

Source: Caribbean Research Council, "Sugar Industry of the Caribbean," Washington, D.C., 1947; J. W. Suryandrayana and P. Sethuraman, "A Decade of Sugarcane Development in Andhra Pradesh," *Indian Journal of Sugarcane Research and Development*, 7:4 (1963); *Annual Report, Bureau of Sugar Experiment Stations*, Queensland, Australia, 1920-64; *South Africa Sugar Yearbook*, South African Sugar Association, Durban, 1934-62.

In all regressions but no. 3, variety change was the change in varietal mix for all varieties:

$$DY = A + b_1 D + b_2 DF + b_3 DR,$$

where

Y = yield
V = a measure of varietal composition based on area planted
F = application of fertilizers
R = rainfall
D = first difference operation, e.g.: $Dy = y_t - y_{t-1}$.

In regression no. 3, the variety variable is the percentage of non-Uba varieties in total production; it is not the percentage change from year to year.

[a] t values are given in parentheses.

The variety change from year to year may be regarded as a kind of measure of "turnover." It is essentially the sum of the changes in percentage of acreage planted to varieties which have increased (or decreased) their share of planted acreage; the results of the statistical analysis are presented in Table 8-5. Fertilizer and rainfall data were not available in all cases. The variety turnover variable has the expected positive sign, and the intercept term has a negative sign. A negative intercept term reflects two phenomena, a natural deterioration of yields owing to disease and other factors, and changing age distribution. As the South African data show, the younger the cane, the higher the

yields. The varietal change measure may be correlated with sugarcane age in these data. A consequence of such a conclusion would be that the intercept term is biased downward and that the varietal change coefficient has an upward bias. Although major changes in average age do not appear to have occurred over the period, we do not have cane age distribution data that would allow us to check this point.

The data in Table 8-4 and 8-5 allow two calculations. The first is the economic value of the activities of experiment stations in speeding up second cycle varietal diffusion. From Table 8-4 we can compute the acceleration or increase in turnover achieved from an investment of $7 thousand (approximately the cost of adding a senior researcher to the staff in 1936). This increase would be approximately .11 percent per year. The value of an increase in variety turnover of .11 percent computed from Table 8-5 is approximately .03 tons per acre in Australia and .02 tons per acre in the Caribbean and South Africa. The total value of this acceleration, resulting from a $7 thousand investment, would be about $50 thousand in Australia and from $12 thousand to $15 thousand in South Africa and the Caribbean area. A reasonable downward adjustment for bias owing to changing age distribution would reduce these estimates by between one-third and one-half.[8] It appears that the "extension type" side benefits from accelerating second cycle varietal diffusion justified much of the investment in experiment stations during the long gestation period before they began producing adapted varieties.

The second computation is the value of adapted varietal output. Research cost data for 1950 can be used to compute the average cost of research per percentage of varietal turnover. These costs were $21 thousand in South Africa, $25 thousand in Australia, and $7 thousand in India. The estimates in Table 8-5 indicate that the varietal change produced by a one-dollar increase in research investment is worth roughly $15 in South Africa, $25 in Australia, and $35 in India (calculations based on estimated coefficients from Table 8-5 and a sugarcane price of $5.50 per ton). These estimates compare current research with current output value. The actual research that results in varietal change requires considerable time. For sugarcane research the average lag is probably at least eight years. Assuming no yield deterioration and an eight-year average lag between investment and benefit realization, the "internal" rates of return are approximately 40 percent in South Africa, 50 percent in Australia, and 60 percent in India. The South African data allow an adjustment for age bias based on a comparison of the Table 8-5 estimates and the comparative data by variety. A downward adjustment of 30 percent is indicated. This adjustment reduces the internal rates of return only slightly.

Rice Varietal Development

Our concern in this section will be with the cyclical nature of rice varietal improvement and with the characteristics shared by both the rice and sugarcane experiences. We draw heavily on the more detailed presentation by Dalrymple in chapter 7. It is useful to consider essentially two major rice economies, one located in the tropical climate zones of the world, the other in the more temperate Mediterranean and Marine climate zones. The two rice economies had independent histories until the 1960s. This independence is primarily the result of the high degree of sensitivity of the rice plant to soil and climate factors.

The temperate zone rice economy, centered in Japan, has a long history of varietal improvement and a consequent record of productivity gains. In some respects it parallels the sugarcane experience with its own cycles and diffusion patterns. The tropical rice zones in Asia's "rice bowl" have quite a different history. For the most part, this region was dominated by colonial relationships of varying types until after World War II. Investment in research directed toward rice improvement was much less intense than it was in the temperate rice zones. And the established research institutes were often designed to serve the interests of the colonial bureaucracy instead of a constituency of rice producers or consumers in the LDC's.

Thus for many years the two rice economies evolved along different paths. With the development thrust of the 1950s and 1960s, several of the new research programs had reached the point where they were capable of incorporating into their own breeding projects the basic scientific advances made in the temperate rice economy. They were slow to exploit the varieties actually produced in their research programs and thus missed the chance to lead the green revolution.

The International Rice Research Institute had a large initial advantage over the fledgling and in some cases bureaucracy-ridden national research programs. It was able to bring together a combination of high-quality intellectual capital (from the temperate zone experience) and to provide the intellectual and moral incentives to direct the work of this group. The resultant discovery of new varieties initiated a major technology cycle in the tropical rice economy.

Cycles in the Temperate Rice Economy

Hayami and Akino offer a useful discussion of productivity in Japanese agriculture (see chapter 2). Hayami and Yamada show that total factor productivity, which is based primarily on rice production, witnessed a distinct period of rapid growth after the Meiji Restoration until about 1920.[9] Then a

period of little or no real growth for ten years or so occurred. This was followed by more rapid growth in the 1930s. Of course, post-World War II Japan has realized a further cycle of productivity gains. (Hayami and Akino compute a specific series on varietal improvement which also shows cycles. This is based on experiment station data, however, which generally has not proven to be an accurate index of real producer gains.)

As several studies of Japanese productivity gains reveal, the early (pre-1920) productivity cycle was based to a substantial degree on the *rōnō* (veteran farmer) rice varieties and production techniques. This is an especially interesting case of technology discovery by highly motivated and inventive farmers which did not depend on sophisticated scientific training. (Interestingly, United States agriculture experienced a slightly earlier productivity cycle based on mechanical invention of a similar nature.)[10] These studies also identify an exhaustion of these potential technology gains from the *rōnō* research methods as the primary factor in the slowdown in growth.

The experiment station system in Japan actually facilitated the diffusion of many of the techniques of production developed by the *rōnō*. In fact, it was primarily through the efforts of research institutions that the technology was diffused to Taiwan. (Again, see chapter 2 for a discussion of the role of the early experiment stations.)

The early experiment station system appears to have lacked the basic knowledge needed to compete with the highly motived and more inventive veteran farmers in the first cycle. By the 1930s, however, the experiment stations had acquired the scientific foundation to stimulate a second productivity cycle in rice production. This cycle was based on varieties and agronomic techniques discovered in the research system. Hayami and Akino (chapter 2) conclude that this second cycle was restricted by the diversion of fertilizer and other input resources for military purposes. They attribute the increased productivity of the experiment station system to an organizational change in which coordinated crop-breeding programs (the Assigned Experiment System) were developed. An alternative hypothesis for the basis for the improvement, which will be explored later, is that researchers acquired an improved understanding of the scientific aspects of crop production.[11]

The diffusion of the Japanese "Japonica" varieties to Taiwan and the subsequent development of the "Ponlai" varieties in Taiwan is an interesting case of the diffusion and adaptation of the Japanese technology. The simple introduction of the Japanese varieties during the 1910-25 period did not result in improved productivity or widespread direct diffusion. Some diffusion was implemented by altering the seedling age at transplanting and by screening for blast resistance, but it was not until the late 1920s that new varieties bred in Taiwan began to have an impact on production. These new ponlai varieties

were then subject to a cycle of their own, which preceded the second Japanese cycle by a few years. Hayami and Ruttan[12] place considerable emphasis on the price-depressing effects of imported rice from Taiwan in slowing down and partly aborting the second rice cycle in Japan.

The diffusion of improved Japanese rice varieties to Taiwan was the forerunner of the more recent cycle in the tropical zone popularly termed the green revolution. In fact, efforts in Taiwan after World War II to breed shorter season varieties and more nitrogen-responsive varieties (the earliness was important in the two-crop rice pattern in Taiwan but not in the single-crop culture in Japan) essentially provided the genetic stock on which the green revolution was based.

Productivity in the Pre-Green Revolution Tropical Rice Economy

N. Parthasarathy, in his review of rice breeding in tropical Asia up to 1960, points out that most Asian countries had some form of breeding and selection work before World War II.[13] The program in India was especially large. It appears that these programs were reduced in effectiveness by breeding work being organized in small isolated stations and by breeding objectives which failed to assign highest priority to yielding ability. That is, breeders attempted to improve seed quality and disease resistance without having real yielding ability to work with. It also appears that breeding work during this period did not even consider fertilizer responsiveness (actual fertilizer use in the region was essentially nil).

After World War II, most Asian countries revitalized and developed expanded rice-breeding programs. An important project to hybridize the Japonica and Indica rice varieties was undertaken in a number of countries in the 1950s. These efforts did produce a number of significant varieties and probably led to some productivity gains. Certain varieties coming from this work are classified as "high-yielding varieties" in some regions today (e.g., Mahsuri which is an important variety in India, though it is actually a Malaysian variety).

In the 1950s and the early 1960s breeders in the tropics began to draw on the technology and scientific base of the more temperate zone experience. It seems incredible now that the great bulk of the plant breeders in tropical Asia missed the opportunity to exploit the fertilizer responsiveness of the plant. Breeders in the Philippines were, however, working on the shorter season, stiff-strawed, fertilizer-responsive varieties. (It is certainly worth noting that superior varieties, particularly C4-63, were produced in the Philippines at approximately the same time as the first IRRI variety.)

The post-World War II breeding programs in Taiwan had developed short-season semidwarf varieties to suit the multiple cropping technology of the

area. This work had markedly reduced the photoperiod sensitivity of the plant. In 1956 the variety "Taichung Native 1" was developed and it has since been diffused to many tropical Asian countries. It became known as a high-yielding variety some ten years after its first release.

The IRRI-Induced Rice Cycle in Tropical Asia

The setting for a major advance in rice-yielding potential and international diffusion of rice varieties in tropical Asia could hardly have been more ideal. The temperate and subtropical research programs, especially in Taiwan, had developed the genetic materials and breeding methods required. The tropical rice programs were bound by tradition and had been slow to learn from the developments in Taiwan and slow to respond to the relative decline in fertilizer prices of the past two decades.

With the establishment of IRRI and the bringing together of a small group of scientists (from the temperate and subtropical zone experience) with the resources and fresh viewpoint of a new institution, it was inevitable that knowledge diffusion would occur. Of particular interest for the stylized cycle model is the apparent diminution in the yield-incremental discoveries by IRRI researchers after IR-8, the first IRRI variety. Essentially, no gain in real yielding ability over IR-8 has been forthcoming to date. The improvements since IR-8 have instead been in three areas: improved grain quality, improved disease resistance, and, most recently, improved insect resistance. Accompanying these varietal gains have been significant advances in related technology.

Another clear characteristic of the IRRI-induced cycle is the diffusion of varieties and genetic materials which has marked similarities with the second cycle in sugarcane productivity. The early diffusion of IR-8, IR-5, and IR-20 was widespread. It was accelerated because a number of international agencies wanted to get on the green revolution "bandwagon." There was then a major push to diffuse the green revolution varieties.

However, in spite of their day-length insensitivity, the IRRI varieties were quite sensitive to soil and climate factors, especially water availability and control. These factors would probably have been sufficient to limit the diffusion of the new varieties to perhaps 20 percent or so of the Asian tropical rice-producing region. The "adaptive" research programs *and* the continued development of the national research programs, which were well underway before IRRI, have expanded the set of high-yielding varieties and extended the green revolution. By 1972-73, some 20 percent of the Asian region had been directly affected. Adaptive research currently under way indicates that the potential area might be in the neighborhood of 50 percent or so.[14]

Wheat Varietal Development

Bread wheat production is effectively undertaken in three relatively independent economic regions: the steppe climate zone spring wheat regions, the steppe climate zone winter wheat regions, and the subtropical-desert climate zone spring wheat regions. Geographically the winter wheat zones tend to be between the two major spring wheat zones. It is not surprising, then, that the steppe spring wheat varietal technology was developed quite independently of the subtropical technology.

No attempt will be made here to detail productivity cycles in the steppe wheat zone or the winter wheat zones. These cycles, especially in the United States, are quite marked. The principal cycle or productivity episode of concern here is the cycle associated with the dwarf wheat varieties in the subtropical zones. This cycle bears certain obvious parallels with the Asian tropical zone rice productivity cycle.

There are, however, a number of important differences in the rice and wheat cases. First, before World War II, very little work on subtropical wheat production had taken place. And developments elsewhere (such as in the steppe spring wheat zone) were not as directly relevant to subtropical production of wheat as was the case with rice. True, the *Norin* 10 dwarf wheats were available by 1935 in Japan, but they were not given much attention until the late 1940s by breeders outside Japan.

The Rockefeller program in Mexico had to support much of the long development process of incorporating desired genetic properties into subtropical wheats. The development of the breeding methodology took time. Because the program has produced a relatively sustained flow of new varieties, it may not be possible to identify real cycles in the Mexican data.

The cyclical aspects of the new wheats in terms of international diffusion closely parallel those of rice, however. The initial degree of superiority of the Mexican wheats over traditional varieties was higher for wheat than for rice, but the same limitations to diffusion imposed by soil and climate factors hold. And the same interactive process in which local or national research efforts have extended the diffusion pattern has taken place in wheat.[15]

Toward Understanding the Basis for Productivity Cycles

Although the foregoing discussion has been heavily descriptive, it has served to raise questions of theoretical importance. Specifically, one is pressed to ask, why the cycles? Why not relatively smooth rates of technology discovery and productivity? Does this reflect inefficiency in the conduct of research?

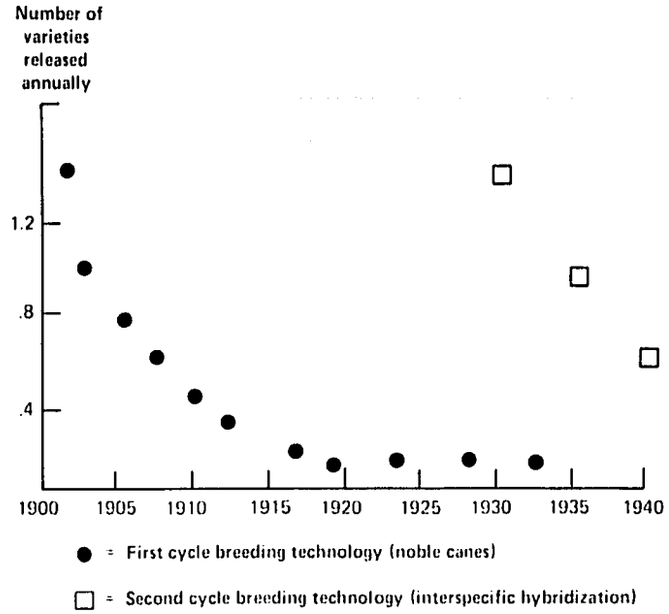


Figure 8-1. Approximate pattern of the release of commercially important sugarcane varieties.

Are there more general inferences about the discovery of technology to be drawn from this evidence?

There is relatively little economic theory which applies directly to these questions. The theory of induced innovation associated with the optimal growth literature and applied to agricultural growth by Hayami and Ruttan does not explain certain shifts in inventive activity which might result in new productivity growth.[16] Some of the crop-breeding literature is at least indirectly relevant. And the economic theory of search and of information is likewise of relevance. These bits and pieces of analytical models can be crudely fashioned to provide at least some insight into the discovery process.

A Simple Search Model

It will be useful to begin to draw upon these concepts by first noting more tangible aspects of the discovery of improved sugarcane varieties in the Barbados Experiment Station. Recall that Barbados scientists shared in the basic discoveries which established the fertility of the sugarcane plant. These discoveries were naturally followed up with a first cycle breeding program where noble canes were crossed and first cycle varieties developed. Later, the station

also produced and adapted second cycle varieties. Figure 8-1 portrays the approximate pattern over time of the release of *commercially important* varieties from the station.

If this measure – commercially important varieties – can be regarded as at least an approximation of the output of economically valuable technology by the station, these data show clear cyclical behavior in technology discovery. The cycles are also clearly related to the basic cane-breeding methodology. The first cycle varieties were produced in the noble cane-breeding program utilizing the limited genetic stock of the eighty-chromosome *S. officinarum* species. It is readily apparent that the ratio of discoveries to discovery effort is declining over time, suggesting an exhaustion of potential.

The Barbados station was relatively slow to introduce the interspecific hybridization breeding program. It began work with this breeding methodology about 1929, several years after the stations in Java and India had established the superiority of the method. From 1929 to 1939 both breeding programs were maintained. As the figure indicates, the interspecific hybridization program was clearly superior. The ratio of the commercial testing stage was 1:1800 for the first five interspecific hybrids and 1:2700 for the next nine. It was only 1:13,000 for the exhausted noble program during this period.

This particular sequence has elsewhere been treated as the consequence of search processes.[17] Only the major features of that analysis will be repeated here (see chapter 10 for an extended treatment of this model). The basics of the search model[18] are as follows.

1. That the scientific knowledge of sugarcane breeders during the 1900 to 1920 period and the genetic materials available to these breeders determined a distribution of potential cane varieties with varying economic values. (Later this will be referred to as the "architecture of search.")

2. That breeders were constrained to search for economically superior varieties within this distribution of potential cane varieties. They became subject to the diminishing marginal productivity of search and had effectively exhausted most of the potential within a few years.

3. That the basic parameters of the distribution of potential cane varieties remained quite stable until the introduction of the interspecific hybridization breeding methods. The decision to shift to the improved breeding system was delayed by the resistance of older scientists to change and by the fact that resources were required to make the change.

4. That the new scientific base created a new distribution of potential varieties with a much higher variance and possibly a higher mean. The consequence of this is that researcher productivity increased markedly. (Note that an increase in genetic diversity will increase the variance of the distribution of potential varieties and the rate of discovery of new varieties.)

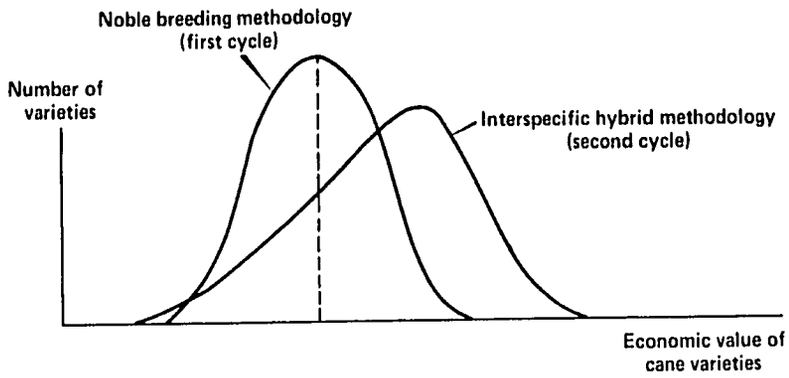


Figure 8-2. Distributions of potential sugarcane varieties.

In other words, search activity undertaken subject to the two potential distributions portrayed in Figures 8-2 and 8-3 is sufficient to generate the data in Figure 8-1.

This simple model of search activity with the somewhat erratic or at least discontinuous shift in the scientific base actually fits most of the cycles described in this chapter rather well. Several relatively straightforward modifications to the model can easily be made.

Productivity of search can be made to be a function of time. That is, the expected discoveries from doubling search activity in one time period will be less than the expected discoveries from the same activities extended over two time periods. Expansion of this concept will lead to optimal search patterns over time.

The search process can be extended to incorporate search over several parameters. In general, a plant variety can be described as a collection of n "traits," each with an economic value. The objective of plant breeders will then be to maximize the change in the total economic value of the traits from one time to the next. Knowledge of the intergenerational heritability matrix, which describes the expected value of the traits in a given generation of plants (or animals) as a function of the selected traits of the parent population, is required for maximization. Incidentally, changes in the economic value of traits will then lead to changes in the mix of traits or characteristics produced as new varietal technology or other technology. It does not follow, however, that the actual rate of change in the trait mix over time will be correlated with initial relative prices of traits.

The search process can be modeled as a more complicated process. Searchers will naturally acquire information about the distribution of potential

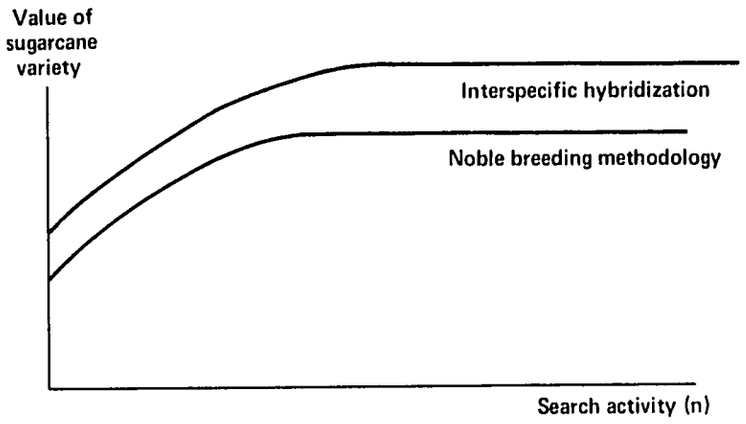


Figure 8-3. Expected maximum value of sugarcane varieties as a function of search.

technologies as they search. At a minimum they will have estimates of the mean and variance of the distribution sufficient to develop "stopping rules." In addition, they will generally be able to sequentially "rule out" unlikely and unpromising directions and areas of search. This sophistication will alter the expected pattern of discovery, but it does not alter the basic exhaustion property.

This type of modeling can be linked to the more conventional growth literature along the lines suggested by Binswanger.[19] Indeed it enriches the induced innovation literature significantly by making it clear that the probability of invention in a particular factor-augmenting direction is a function of the "state of exhaustion." Hence the simple propositions regarding a relationship between factor augmentation bias and factor prices do not hold.

Dynamic aspects of the model can be explored along the lines investigated by Kislev (chapter 10).

Even with such complexities, this approach is still limiting in at least two respects. It does not explain why the scientific base for technology discovery, which originates the cycles, shifts in a discontinuous fashion. And it does not deal with the question of the diffusion of technology to producers facing different environments.

Discontinuities in the Growth of Scientific Knowledge

Searchers for technology, of course, are not indifferent to the state of scientific knowledge. Nor is the inference that research personnel can be con-

veniently categorized as searchers for technology or as searchers for scientific knowledge justified except in relatively primitive research systems. A primitive system will tend to be organized as two distinct systems, one for technology search and another for scientific knowledge search. The skill mix and administration within each system constrain their output to simple search activity, and they are particularly subject to the exhaustion phenomenon. Such systems produce little new technology or scientific knowledge except as they adapt it when it is introduced from outside the system.

In more advanced systems, one finds a more complex organization. In particular, as the skill mix is increased, new specialities and motivations are developed. In chapter 15 Swanson discusses the role of the "biological architect" in designing and improving search methodology. One could expand this concept to incorporate other types of architects in the physical and social sciences as well. These architects play a key role. Their design activity is fundamental to the implementation of scientific findings. In addition, they serve to direct and orient scientific discovery toward economic objectives.

Within professional and academic circles, there are powerful social incentives to belong to either an elitist scientific organization or a professional society. The biological architect does not fit well in either. These interests tend to be built into graduate programs in the agriculturally related sciences.

The history of most agriculturally related scientific systems clearly shows that the classical organization of scientific discovery was poorly suited to the development of either the technology searcher or the biological architect. Agriculture and engineering research required the creation of separate and competing systems. The land grant system of the United States appears to have been reasonably successful in bringing about the integration of science and technology, but most developing countries have not achieved this.

A basis can be found in this discussion for the high degree of sensitivity to exhaustion which appears to characterize the agricultural research systems of developing countries. The skill mix required for a more advanced organization is such that it is likely to be some time before many systems in the tropics mature to the point where these factors will be less important. It should be expected then that real changes in the scientific base will tend to be discontinuous in research systems without large numbers of skilled and motivated scientific architects.

The Diffusion of Technology and Knowledge

The diffusion of specific items of technology across regions is clearly related to a range of soil, climate, and economic factors. Virtually all forms of technology, and especially those in agriculture, are sensitive to these factors in that minimum average costs (excluding rents to fixed factors) of produc-

tion with any particular set of techniques will change when production is undertaken under other conditions. A particular variety of rice, for example, performs well on one type of soil and poorly on another.

Consequently, for every possible set of soil, climate, and economic conditions, there exists *in principle* a *unique* set of technologies for most efficient production. Thus, if it did not cost anything to tailor technology to environmental factors, agricultural technology would be immensely rich in detail. An improvement in one particular item of technology would temporarily be diffused over a limited range of environmental factors, but researchers would then adapt and tailor the improvement so that, when a new equilibrium was reached, every environment set would have a unique technology set. In such a world, technology diffusion per se would be virtually nil and would only exist because adaptation took time.

Obviously, in the real world, adaptation is a costly process, and as a result technology is not tailored to every environmental detail. Some degree of tailoring to "aggregated detail" will hold.[20] Nonetheless, the costless tailoring case affords some insight into the diffusion patterns described for sugarcane, rice, and wheat. It is consistent with the temporary character of direct technology diffusion and the inducement given to adaptation.

With costly adaptation, research systems will be designed to take into account both the supply of research skills and environmental conditions. The scarcer the high-level skills of the biological architect, the more efficient it is to design systems purely to undertake a low-level adaptive function based on simple search activities. Such systems have few scale economies to particular experiment stations and consequently are usually designed to achieve a high level of tailoring. Generally one finds a proliferation of small research units under these conditions. These systems are dependent on "mother" institutions for genetic material and search design.

When higher levels of skills are available (and not "wasted" in administrative tasks), the efficient system will have some biological architect capability and will be somewhat independent of other systems. It will sacrifice tailorability to realize the gains to be had from its independent "architect" capability. Because isolation is more costly in such a system, it will tend to have fewer experiment stations. Naturally the system will undertake adaptive research, but it will tend to be much more productive than the purely adaptive systems.

The adaptive research process is, of course, itself a diffusion process. Knowledge of some type is being diffused. Scientific equipment and genetic material can be considered to be forms of embodied knowledge. Knowledge is also sensitive to soil, climate, and economic factors. The physiological relationships of the rice plant in the temperate zone are sufficiently different from

these relationships in the tropics. New knowledge for the tropics must be discovered independently of the temperate zone stock of knowledge. In this context, the tropical zone system requires a high level of biological architect capability to achieve this discovery.

Concluding Comments

This chapter offers neither a thorough historical study of technical changes in sugarcane, rice, and wheat nor a strictly formal treatment of the process of technology discovery. It has attempted to draw inferences from certain observable aspects of technical change which have relevance for the eventual formal models of technology discovery. No doubt many points of interest have been missed, and at least some of the inferences and interpretations are subject to improvement. But one must begin somewhere. The failure to understand even the basics of technology discovery and its diffusion has plagued developed programs for years.

In this chapter, observed cyclical behavior in realized productivity gains and in tangible measures of technology discovery has served as a basis for inferences regarding the role of scientific knowledge. This knowledge was interpreted as the architecture of the process of searching for technology.

Development literature generally attributes much less importance than has been given here to the role of scientific knowledge. In particular, although there is probably general agreement that little direct diffusion of technology between widely different climate zones takes place, the presumption that scientific knowledge is widely diffused appears to be maintained. The interpretation given to the record of sugarcane, wheat, and rice technology in this chapter is that the diffusion of knowledge is also limited by soil, climate, and economic factors. A full test of the implicit alternative hypotheses put forth in this chapter, however, awaits both better measurement and better theory.

NOTES

1. This section draws heavily on an earlier paper by R. E. Evenson, J. P. Houck, Jr., and V. W. Ruttan, "Technical Change and Agricultural Trade: Three Examples -- Sugarcane, Bananas and Rice," *The Technology Factor in International Trade*, ed. R. Vernon (New York: National Bureau of Economic Research, Columbia University Press, 1970), 418-483.

2. See W. R. Akroyd, *The Story of Sugar* (Chicago: University of Chicago Press, 1967); A. C. Barnes, *Agriculture of the Sugar Cane* (London: Leonard Hill, 1967); A. R. Grammer, *A History of the Experiment Station of the Hawaiian Sugar Planters Association, 1895-1945*, Hawaiian Planters Record no. 51 (1947), 177-228.

3. G. C. Stevenson, "Sugar Cane Varieties in Barbados," British West Indies Bulletin no. 39 (Barbados: British West Indies Central Sugar Cane Breeding Station, 1968).

4. A. J. Mangelsdorf, *Sugar Cane Breeding in Hawaii, Part I, 1778-1920*, Hawaiian Planters Record no. 50 (1946), 141-160. *Sugar Cane Breeding in Hawaii, Part II, 1921-1952*, Hawaiian Planters Record no. 54 (1953), 101-137.

5. It was shortly after this that Shull and East in the United States used the same principle to develop the "hybridization" of corn. See Stevenson, "Sugar Cane Varieties."

6. E. P. Alvord and G. Van de Wall, *A Survey of the Land and Feed Resources of the Union of South Africa* (Pretoria: J. L. Saik, 1954); M. H. DeKock, *Economic History of South Africa* (Johannesburg: Juta, 1924).

7. Boris C. Swerling and Vladimer P. Timoshenko, *The World's Sugar* (Stanford: Stanford University Press, 1957).

8. The South African yield-by-age data indicate that a 1 percent increase in plant cane, over and above the normal increase needed to maintain the average age, would result in an increase in average yields of about .2 tons per acre. This is the maximum adjustment which might be made. It would represent about one-third of the Australian yield effect and all of the Caribbean and South African effect. The South African coefficient is approximately what it should be according to the yield comparison da. .

9. Yujiro Hayami and S. Yamada, "Agricultural Growth in Japan, 1880-1970," *Agricultural Growth in Japan, Taiwan, Korea and the Philippines*, ed. Yujiro Hayami, Vernon W. Ruttan, and Herman Southworth (Honolulu: University Press of Hawaii, in press).

10. Robert E. Evenson, "The Green Revolution in Recent Development Experience," *American Journal of Agricultural Economics*, 56:2 (May 1974), 387-394; D. D. Evenson, D. J. Martin, and Robert E. Evenson, "Inventive Activity in U.S. Agriculture, 1890-1940: Lessons for Developing Countries," Economic Growth Center, mimeographed (New Haven: Yale University, 1974).

11. Okabe attributes the success of the experiment stations in the second cycle to the result of ecological breeding. In other words, the experiment stations could compete with the veteran farmer only by utilizing their selection procedures. S. Okabe, "Breeding for High Yielding Varieties in Japan," *Rice Breeding* (Los Baños: International Rice Research Institute, 1972), pp. 47-60.

12. Yujiro Hayami and Vernon W. Ruttan, *Agricultural Development: An International Perspective* (Baltimore and London: Johns Hopkins Press, 1971), pp. 198-212.

13. N. Parthasarathy, "Rice Breeding in Tropical Asia up to 1960," *Rice Breeding* (Los Baños: International Rice Research Institute, 1972), pp. 5-30.

14. See chapter 9 in this volume. Also Dana G. Dalrymple, *Development and Spread of High-Yielding Varieties of Wheat and Rice in the Less Developed Countries*, Foreign Agricultural Economic Report no. 95 (Washington, D.C.: Economic Research Service, USDA, 1974).

15. Evenson, "Green Revolution in Recent Development Experience."

16. Yujiro Hayami and Vernon W. Ruttan, *Agricultural Development*.

17. Robert E. Evenson and Yoav Kislev, "Investment in Agricultural Research and Extension: A Survey of International Data," *Economic Development and Cultural Change*, 23 (April 1975), 507-521. The data in this article have been further extended in James K. Boyce and Robert E. Evenson, *National and International Agricultural Research and Extension Programs* (New York: Agricultural Development Council, Inc., 1975).

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9

Comparative Evidence on Returns to Investment in National and International Research Institutions

Robert E. Evenson

Agricultural research institutions in the developing countries have undergone marked changes in organization and support in the past twenty-five years. In the 1950s, most development programs were designed with the expectation that it was possible to achieve low-cost diffusion of much modern (developed country) technology to the developing economies. Major development aid was given to extension, credit, and community development programs. During this period, investment levels for agricultural research in developing countries were roughly one-half the levels for extension. This was in sharp contrast to investment patterns in the developed countries, where the level of investment in agricultural research was at least double that in extension.[1]

Financial support for buildings, equipment, and project financing from international aid agencies in the late 1950s was on the order of $50 to $60 million annually. This represented more than one-third of the total resources directed toward agricultural research in the developing world at that time. In addition, large numbers of technical advisers, visiting professors, and other personnel were located in developing countries. Hundreds of scholars from developing countries were provided with support for graduate study in universities in developed countries.

During the 1960s these patterns changed markedly. A number of appraisals of the developing-country research and extension programs led policy makers to the conclusion that neither the research nor the extension systems were ef-

fective. The problems involved in simple technology transfer were beginning to be recognized, and the failure of the extension systems to produce change were properly attributed to the paucity of real technology to extend. The fledgling research systems in developing countries were seen as lacking in scientific skills, subject to bureaucratic rigidities, and misguided about their objectives. By 1970, international financial support to the national research systems had declined, as had support for international scientists and technical personnel located in the LDC institutions.

While this decrease in support for national programs was taking place, the basis for a significant subsequent development was being laid. This was the establishment, by the Rockefeller and Ford foundations in cooperation with host governments, of two international crop research institutes: the International Rice Research Institute (IRRI) in the Philippines in 1962 and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1966. Several other such institutes followed in the late 1960s. The United States government began to provide financial support in 1969 and 1970. Significant international support for these and other international centers began in 1972 through the newly established Consultative Group on International Agricultural Research.

Many observers have concluded that the shift in emphasis to international agricultural research showed extraordinarily good judgment, perhaps the best in regard to the allocation of development resources since World War II. This feeling was particularly prevalent in the late 1960s and early 1970s, the heyday of the green revolution. The success of the IRRI rices and the Mexican dwarf wheats and the adoption rates and increased production breathed new life into many development programs. The subsequent slowdown in the rate of growth of yields, however, and the failure to realize some unwarranted expectations have resulted in an equally unwarranted state of pessimism regarding future productivity gains.

This recent history tells us a great deal about the process of change in agriculture, about the factors which alter the probabilities of discovery of new, more efficient methods of producing food and fiber, and about the factors that determine the diffusion of such methods across regions. We are still at a primitive stage in our ability to analyze this experience. We have now accumulated what appears to be an impressive collection of "rate-of-return" studies, all of which show extraordinarily high returns to investment in research. Some advances have been made in modeling discovery processes and invention. And the roles of climate, soil type, and prices as determinants of the diffusion of technology have been clarified in recent studies. But in spite of this, we remain some distance from a fully convincing theory of technology discovery.

Rate-of-return estimates have been useful in establishing certain basic propositions regarding the productivity of research. Unfortunately, the available estimates have been abused in policy discussions. The inconsistent citation of extraordinarily high rates of return – especially the oft-quoted 700 percent return on hybrid corn research – has left the impression that the estimates themselves are subject to such a degree of error that only those above 100 percent or so are really significant! This is somewhat similar to the old notion that farmers would not adopt a new technology unless the new technology possessed a degree of superiority of 75 percent to 100 percent over the technology in use. This simply has not been true. Such studies err primarily in their estimation of the real degree of superiority of the new technology.[2]

This is a serious matter because some of the estimates have been derived through the use of systematic econometric formulations, and standard errors have been estimated and reported. Others have simply been computed using, in most cases, supposedly "conservative" assumptions designed to ensure a downward bias in the estimate. Still other computations have been based on costs and benefits of entire research programs.

The computation of rates of return to investment in national and international research without a systematic, if crude, analytic framework provides little useful information to policy makers. Policy issues cannot be effectively addressed with one or two simple estimates. They involve some fundamental questions regarding the externalities attendant upon the diffusion of technology and scientific knowledge between regions. The knowledge that an investment of $10 thousand or $100 thousand in research on sorghum technology will yield an expected 50 percent internal rate of return is not very useful if one cannot say something about the incidence of the research consequences. If a country makes the investment, how much will its producers or consumers appropriate? And how much can they get for nothing, from research undertakings in other countries?

The body of existing economic theory does not provide ready answers to these questions. But enough work on the topic has now been completed to develop partial theoretical and empirical formulations which at least are cognizant of major features of the underlying processes. In the first two sections of this chapter some of those issues are discussed and reviewed. An econometric study of the contribution of research is then reported. The final section develops some of the policy implications.

Elements of a More Systematic Formulation

As a starting point, it will be useful to classify the different skills involved in the discovery of new production technology. This classification will help in

understanding the constraints imposed by supply conditions of different types of skills, because there is a close relationship between skill types and efficient organization of research activity. A degree of arbitrariness attends all classification schemes, and the categories of skills proposed here are intended only to capture major features.

A Typology of Researcher Skills

Skills of relevance in research institutions can be classified in the following categories.

Inventive skills. Inventiveness has distinguished all developed societies and is a fundamental human characteristic. Effective application of inventive skills does not always require highly developed skills of other types. A great deal of the mechanical invention relevant to agriculture was undertaken by farmers, mechanics, and blacksmiths without formal training in engineering. Even in some biological technology fields, inventive ability can be sufficient to produce significant new technology, as when the *rōnō* (veteran farmer) selected rice varieties in Japan.

Technical and engineering skills. Professional undergraduate programs in engineering and agriculture seek generally to produce technical competence. Not all programs achieve this, but many succeed in establishing a basic ability to apply certain well-established "textbook" principles to technical problems. It is significant that the supply conditions in many developing countries are such that the research personnel in many research institutions have only the latter capability.

Technical-scientific skills. Technical-scientific disciplines such as agronomy, plant breeding, and agricultural engineering have evolved over the years and form the core of graduate programs in the agricultural sciences. Some of these disciplines bear a close relationship to a classical scientific discipline; others have developed as "interdisciplinary" fields. They vary greatly in their intellectual rigor and degree of closeness to a "scientific frontier of knowledge." Most have legitimate scientific frontiers of their own, but these tend to be closely associated with and form part of more general scientific frontiers.

Most M.S. programs and many Ph.D. programs in the agricultural sciences impart technical-scientific skills. These skills go beyond technical understanding and involve a degree of scientific abstraction. That is, they include the ability to generalize and to conceptualize in abstract terms. This skill category is designed to capture both high-level technical and limited conceptual skills.

Conceptual-scientific skills. Experience at the scientific frontier is required for the development of a high level of conceptual skills. Graduate programs

and associated research experiences at the Ph.D. level attempt to develop those skills. Many programs do not accomplish this, however, either because a significant frontier in the discipline is lacking or because a program does not provide the opportunity to acquire the technical or "tool" skills sufficient to permit work at the frontier.

The observed output of scientists with these skills may primarily be in the form of published *scientific studies*. That is, many will not produce *technology* and will not attempt to do so. They will have the depth of understanding necessary, however, to direct their work toward the overall design and other features of technology discovery systems.

Experience at the scientific frontier is extremely important in providing leadership and the design of research activities. Many "successful" agricultural scientists have shifted their work from the scientific to the technology frontier during their careers. Few have managed to remain at the scientific frontier for long periods of time. Some of those who have not opted to move to the technology frontier have continued to be effective teachers to students.

This typology of skills is somewhat general and could be applied, with minor modifications, to systems oriented toward engineering technology or medical technology. A similar typology for the classical science institutions could be developed as well.

Skills and Institutional Organization

The discussion of skills is relevant to the comparison between national systems in developing and developed countries and the international institutes because supply conditions of skills vary greatly between these systems. Inventive skills are generally abundant in most societies, but their exercise in pursuit of new technology depends on a number of factors. Technical and engineering skills are relatively abundant in developing countries, but technical-scientific skills are in very limited supply and conceptual-scientific skills are almost nonexistent in some countries.

A correlation between research system organization and the supply of skills is apparent in both historical and international cross-sectional evidence. Again, at the risk of oversimplification, a stylization of this relationship would be useful.

Low-skill level systems. Typically, in the agricultural research systems that rely primarily on technical and engineering skills, experiment stations are widely diffused and tend to be commodity-oriented. Field trials and experiments tend to be "cookbook" in nature, since little real capacity to design flexible and changing methodology exists. Stations tend to be small and seldom have strong ties with graduate teaching institutions. The system attempts

to take advantage of the opportunity to undertake pure adaptation of technology exogenously delivered to it.

Intermediate hierarchical systems. As appreciable technical-scientific and some conceptual-scientific skills become available, hierarchical systems tend to emerge and specific institutions assume leading roles. These stronger institutions respond to the economies of concentration and in many cases to the complementarities between graduate teaching and research. Economies of concentration are based on the capacity to exchange knowledge with other institutions and to create and modify the basic research designs or the "architecture" (as suggested by Swanson in chapter 15), of the research program.

Generally, one observes a move to consolidate and "coordinate" the diverse, isolated station programs. A main station-branch station system tends to emerge with a high degree of centralized control. The central or main stations develop some capability to engage in independent as opposed to primarily adaptive research.

Advanced science-based systems. As the supply of conceptual-scientific skills increases, agricultural research systems are more often organized to take advantage of economies of "scale" based on communication and the exchange of knowledge. Stronger ties to disciplines and to scientific frontiers are maintained, and most institutions exploit the complementarities between graduate teaching and research. Indeed, institutional quality is most often judged on the strength of graduate teaching and the ability to produce original Ph.D. dissertations.

Branch station systems generally are consolidated and as a rule serve very minor functions in the research programs. In such systems, technical-engineering skills are utilized in a purely operative fashion. Low-level technical-scientific skills (masters' level) are of little value if higher level skills are available. The highly regarded stations are leaders in refining theory, and research that does not have direct technological objectives is recognized as a vital and important part of the process.

Technology Diffusion, Knowledge Diffusion, and Organization

The sensitivity of virtually all forms of agricultural technology to soil, climate, and economic factors has influenced the organization of agricultural research systems. Indeed, the scattered experiment station organizations under low-skill-level conditions are designed to adapt technology to relatively minor gradations in soil, climate, and economic conditions. If there were no economies to the concentration of research skills (and there are few with technical and engineering skills), agricultural technology would be extremely rich in variety. Each minor gradation in soil, climate, and economic condi-

tions, each "ecological niche," would have a unique set of technologies. Its adapted technology set would be superior to any other, and no opportunity for diffusion of technology from one niche to another would exist.

Furthermore, when new technologies were introduced from outside, diffusion across niches would be temporary in character. It would always be possible in each niche to discover an adaptation which would be superior to the imported technology. The diffusion of technology in the simplest sense of the term would not take place. In fact, of course, agricultural research systems are neither geared to tailor technology to minor niches nor capable of adapting all technology quickly. An appreciable amount of unrefined direct technology transfer does, necessarily, take place.

The low-skill-level systems with only adaptive capability are dependent on the diffusion to them of technical and engineering knowledge. They have sufficient skills to conduct agronomic trials and to participate in simple plant-breeding and selection programs. If "mother" institutions feed them new genetic material and new fertilizers, chemicals, and machines, they can be productive in adapting and modifying this particular form of knowledge.

The niches to which technology is tailored are based on gradations in the relevant soil, climate, and economic factors. Niches are not necessarily geographically contiguous, though an attempt is made to locate experiment stations where they will produce adaptations suited to modal conditions within the niche, in order to maximize the economic value of these adaptations.

Main stations now engage in a more complex form of knowledge diffusion. They have some capability for feeding technical and engineering knowledge to the branches. This capability depends on their own ability to scan other regions for technical and scientific knowledge. To some extent, scientific knowledge may be fed to the branches (to improve field plot design, for example) but its primary benefit is the facilitation of *independent* technology discovery on the part of the main station. This is a kind of high-level adaptive research.

In a research system with significant conceptual-scientific skills, research organizations develop complex specializations and explicitly seek to produce scientific knowledge. It is in these stations that the stock of knowledge which serves as a foundation for the design of technology discover systems is itself discovered and conceptualized. Much of this design work requires a thorough understanding of scientific facts and generalizations and experience at the frontier. The capacity to be an "architect" thus is developed in graduate schools, though some research experience is also required. Consequently much of the contribution of the science-oriented research and graduate teaching center is in the form of the intellectual capital created in graduate training.

Diffusion of knowledge has been a significant part of all types of research systems. In low-skill systems this has been primarily diffusion of technological and engineering knowledge in which a "disclosure" effect was involved. That is, the simple disclosure of the feature of new technology is sufficient to guide researchers toward further improvements. In more advanced systems, more abstract knowledge is diffused as well (see chapter 8).

The Role of the International Centers

With the exception of CIMMYT and IRRI, most international centers are still in a relatively early stage of development and have yet to establish a place in the research systems of the tropics. Both CIMMYT and IRRI have clearly established themselves as dominant centers as far as the capability to produce both new technology and new technical and engineering knowledge is concerned. The establishment of this dominant position by both institutions was based on two factors: imaginative administration and researcher support, and the intensive application of conceptual-scientific skills in the research program. One or both factors were, by comparison, usually lacking in the national research programs in the tropics and semitropics.

The emergence of the international centers for wheat and rice research has markedly changed the relationship between national research institutions. In a crude sense, the "main" stations in national research programs have become "branches" to either CIMMYT or IRRI. That this should happen in the short run appears to be inevitable. These centers are producing superior varieties and superior genetic material which virtually all national programs find of use in their own breeding programs. In the long run this will change as national experiment stations are able to mature into more independent institutions.

The emerging international hierarchical system in which national research systems are to a considerable extent dependent on the international centers is based only in part on the relative strength of skills in the institutions. In the past few years a new element has entered the picture. It is best seen in CIMMYT's international breeding programs (see chapter 13). With the systematic use of international sites in breeding programs, incentives exist for the development of a simple service-oriented hierarchy. It appears that CIMMYT wheat breeders are convinced that the broad-ranging breeding program is paying off. It is not surprising then that CIMMYT is primarily interested in training researchers who will both service the international programs and be fed from the center (see chapter 15). IRRI appears to be moving in a similar direction (see chapter 12).

Implications for Econometric Investigations

The major implications of the foregoing observations for econometric studies are the following:

1. An attempt to distinguish between the different types of skills should be made. These skills enter the "technology production function" in different ways.

2. A simple geographic correlation of research investment (or a research capital stock) and productivity is not an adequate specification.

3. "Average" products for research investment are generally meaningful only in a historical sense. As with any average product, they have limited relevance to policy. In certain simple models they are easier to estimate than marginal products, but in models of the type that we are dealing with here the more conventional marginal product of "research capital" formulation is the appropriate model.

4. International data are required to identify patterns of knowledge diffusion. This forces the analyst to face up to the problems of utilizing such data and devising models accordingly. It is just not possible to investigate this issue with ideal data.

An approach which is tractable, given available data, is to utilize a basic "determinants-of-productivity-change" model in which several types of research capital variables are included. These are as follows:

1. Technology-oriented research conducted in the country or region on which the observation is based.

2. Science-oriented research conducted in that country. Note that this is agriculturally related science, not classical science as taught in the liberal arts college. It includes plant physiology, plant genetics, experimental design, microbiology, and the like.

3. Technology-oriented research in *other* countries or regions of sufficient ecological similarity that diffusion of technical and engineering knowledge is possible. Some of this may be diffused in the form of direct technology transfer, but the bulk of research should be expected to induce adaptations by disclosure. Ideally, a continuous measure of degree of similarity should be used to define similar regions. As a practical matter at this point, one has to rely on climate classification schemes to define this variable.

4. Science-oriented research in *other* countries of ecological similarity such that scientific knowledge transfer can be expected. The diffusion of scientific knowledge takes place over a much broader range of conditions than is the case for technical and engineering knowledge.

5. The contribution of the international institutes should be treated as a temporary departure from the basic developing-country research process. This is the case only because of the timing of the discovery process. Had the investment in the research leading to the improved wheat and rice varieties been greater and earlier, their development would not have resulted in a revolution but would have been part of the larger pattern of technology discovery.

*Empirical Studies Based on Diffusion and Skill Specifications**

Relatively few studies utilizing the family of specifications suggested in the preceding section have been undertaken. In fact, only three or four studies utilizing international data have been reported. And the utilization of geoclimate data to specify an implicit relationship of knowledge transfer is also confined to a very few studies.

The Early International Studies

The first international study of factors influencing relative efficiency was reported by Hayami and Ruttan. This pioneering study established the feasibility of utilizing an international "meta-production function" as a tool of analysis.[3] At the time of this study, however, a set of reliable international data on investment in research was not available. Hence the inferences regarding the role of research and related investment were quite general.

With the availability of internationally comparable data on research and extension investment, new possibilities have been opened up. Evenson and Kislev report an extension of the basic Hayami-Ruttan results based on updated data and the specific inclusion of a research capital variable.[4] Their study reported estimated marginal internal rates of return of 42 percent to technologically oriented research in developing countries and 21 percent in developed countries. The study also computed an indirect rate of return to related scientific research of 60 percent for the developing countries and 36 percent for the developed countries. These results, while based on quite aggregate data and indirect methods, foreshadowed those obtained in later work (reported below).

Geoclimate Specifications

Perhaps the more important specification improvement, however, was the development of knowledge transfer specifications. The first study to utilize geoclimate regional data was an international study of wheat and maize productivity.[5] The basic model utilized in the study specified that productivity in a country (measured by yields) was causally related to country-specific factors, weather effects, the stock of knowledge created by indigenous wheat (maize) research, *and* the stock of knowledge extant in other countries with similar geoclimate conditions. That is, in this model a country could benefit from research undertaken in other countries. The mechanism was essentially what has been described here as the transfer of technical-engineering knowl-

* This section has been abridged. A number of the author's original technical discussions and tables have been eliminated in order to simplify and shorten the presentation. Further details are provided in Appendix 9-1 and in references cited by the author. – Ed.

edge with a disclosure effect. This study imposed complementarity between the indigenous stock of knowledge and the borrowable stock of knowledge. The results showed that countries without the capability for significant indigenous research realized almost no transfer benefits. High returns to the research activities were computed. Research was shown to be productive by leading directly to improved technology and by facilitating technology transfer.

This basic model has been utilized in two studies of national research programs. The study of most relevance here was based on Indian data.

The Indian National Study

The case of India is an especially relevant national system. It could probably be categorized as an intermediate-skill-level system of a basically hierarchical nature. Relatively few national systems in developing countries are as advanced.[6]

An analysis of crop-related research expenditures by states shows that the government has pursued significantly different research investment programs in the several states in India. The results of the study indicate that an increment to the state *research* capital stock of 1,000 rupees is associated with a direct increase in the value of agricultural product of 6,600 rupees. An additional contribution of 1,300 rupees is forthcoming through interaction when extension activity (at the mean level) is undertaken. An increment of 1,000 rupees to the research capital stock cannot be obtained by increasing investment in research in the most recent years, because of the distributed lag construction. Thus the 7,900 rupees (6,600 + 1,300) can be viewed as the level to which the generated income stream grows after the distributed lag period. Consequently the 7,900-rupee income stream represents a 46 percent internal rate of return. (The "time shape" of the benefits is discussed in a subsequent section.) The same increment to the research capital stock is associated with an additional 800-rupee income stream owing to the acceleration of knowledge transfer.

A 1,000-rupee increment to investment in *extension* capital generates an income stream of 175 to 200 rupees. With a short time-lag between investment and the realized income stream, this represents a relatively normal rate of return of 12 to 15 percent. A related study of Indian productivity, based on district data designed to measure the contribution of the Intensive Agricultural Districts Program, indicated that the return realized on the resources devoted to extension and general development activities under the program was also approximately 15 percent.[7]

The Indian study serves to demonstrate that knowledge transfer between

regions can be identified with the geoclimate data. It also provides hard evidence that national research systems like those in India are, indeed, productive. (However, the fact that they are productive does not necessarily mean that they are efficient.) Data from one country, even one as large as India, are not entirely adequate to investigate the larger question of knowledge transfer. Nor was it possible with the Indian data to explore the issue of the relative contribution of different types of knowledge procured by different types of skills.

Productivity in Cereal Grains

An international study of cereal grain productivity reported by Evenson attempted to explore further both the issue of international knowledge transfer and the question of the relationship between different types of knowledge.[8] The study is of particular interest in the context of this chapter in that the contributions of the high-yielding varieties (HYV's) produced in part by CIMMYT and IRRI are incorporated into the model. A rough measure of the relative marginal contributions of additional investment in national versus international research programs and in technology-oriented versus science-oriented research activities is possible. In addition, it is possible to distinguish gains appropriated by the investing country from those accruing through knowledge transfer to ecological neighbors of the investing country.

This study does have data limitations. It is not possible to obtain measures of several conventional factors of production. One cannot know how much labor or machine service was devoted to the production of specific cereal grains. Many studies of agricultural productivity have utilized the simple measure of partial productivity – production per unit of land. It is, on the whole, not subject to serious error as an index of efficiency gains over time, but it is not an ideal measure. Fortunately, it was possible in this study to add a second factor, fertilizer use, to the analysis.

The methodology and findings of the study are presented in Appendix 9-1; the implications will be outlined below.

Economic Implications for Research Investment

The several studies reviewed here have considerable significance for the productivity of research. They may be summarized in the form of estimated marginal benefit streams associated with an increment of $1,000 to the research capital stock. These are not the usual calculations of average product type. The reader can convert the streams into rates of return or cost-benefit ratios as desired. If the increment of $1,000 to the capital stock is viewed as being distributed over time according to the construction of the stock, the time shape of the return is as shown in Figure 9-1. Investment in time t pro-

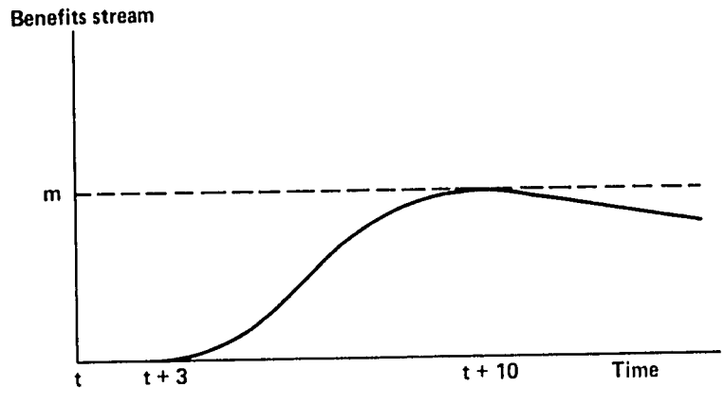

Figure 9-1. The timing of research benefits.

duces an expected stream beginning in year t + 3 and rising to the level m by year t + 10. Since technology is subject to depreciation, it is quite possible that gains once realized will be lost. The decline after year t + 10 reflects this possibility.

Table 9-1 summarizes the economic implications of the cereal grains study. In the first part of the table, computations based on the cereal grains regressions in Appendix 9-1 are presented. These computations are relevant to investments in national systems. The developing-country computations are based on a regression excluding the HYV variables (see Table 9-6 in the appendix) on the grounds that it measures a more stable long-run relationship. If they were to be based on the HYV regression they would be slightly lower.

One of the advantages of the particular functional form utilized is that one can estimate how much of the expected generated income stream is appropriated by a typical investing country and how much flows to ecological neighbors. This, of course, depends on how much research the neighbors do. The computations in part 2 of Table 9-1 are based on mean level of research capital in neighboring countries.

The relative size of the estimated income streams in developed and developing countries should not be surprising. It does not indicate that researchers in developing countries are more efficient than those in developed countries. It reflects two factors. First, developing-country research skills are relatively low-priced; they cost less than half what they cost in developed countries. The research measure utilized partly corrects for this. Second, and more importantly, the size of the streams reflects that the ratio of research capital to conventional factors of production is only one-fifth as high in the develop-

Table 9-1. Estimated Marginal Benefit Streams Associated with National Research Investment of $1,000[a]

Benefit Streams	Research Investment			
	Developed Countries		Developing Countries	
	Technology-Oriented	Science-Oriented	Technology-Oriented	Science-Oriented
Part 1				
Appropriated by investing country				
(a) Direct contribution	$ 630	$12,300	$ 3,710	$35,600
(b) Through complementarity with research in other countries	1,620	1,620	7,200	7,200
Total appropriable benefits	$2,250	$13,920	$10,910	$42,800
Part 2				
Contributed to other countries[b]	5,150	17,000	49,000	37,300
Total international benefit stream (Part 1 + Part 2)	$7,400	$30,920	$59,910	$80,100
Part 3				
Realized by a typical country from research investment by other countries in similar climate zones (or regions)[c]				
(a) With average indigenous research capability	$8,580	$ 520	$55,000	$ 1,700
(b) With no indigenous research capability	$4,560	$ 520	$ 1,700	$ 1,700

Source: Computations were based on cereal grains research regressions (1) and (2) in Table 9-6 (Appendix 9-1).

[a] Estimated levels, in 1973 United States dollars, to which benefit streams associated with a research investment of $1,000 will rise eight to ten years after initial investment. If a normal 12 percent rate of return is realized, the level will be approximately $1,000. A 20 percent compound internal rate requires roughly a $3,000 stream and a 50 percent rate requires $16,000. It is useful to think of this investment as a purchase of income streams or as a purchase of economic growth. The price of the streams is the inverse of the internal rate of return.

Computations were based on mean values of variables in the derivatives from the two data sets. The derivatives are in terms of the effect on production of a change in the knowledge stock. The knowledge stock is converted from publications to dollars, based on the data in Robert E. Evenson and Yoav Kislev, *Agricultural Research and Productivity* (New Haven: Yale University Press, 1975), chapter 2, Table 2.4. Arithmetic rather than geometric means were utilized in the computations on the grounds that they are more representative of typical countries. Cereal grain product is valued at $80 per metric ton (approximate 1971 prices).

[b] Contributions to other countries were based on the average number of other countries in similar regions for T (0.6 in developed countries, 0.9 in developing countries), and zones for S (33 for developed countries, 23 for developing countries) (see Table 9-8).

[c] Benefits realized from other countries were computed as the marginal products of regional research. 3(b) was computed setting indigenous research equal to zero. Note that the construction of the model is such that the contribution of zonal science-oriented research depends only on regional research and not on indigenous research.

ing countries, so that marginal products of research will be high for this reason if standard production relationships hold (see chapters 8 and 10).

The fact that the science-oriented research should be more productive than the technology-oriented research is also not surprising. It reflects that conceptual-scientific skills in the developing countries are scarce and have high value. Actually, the special nature of the research capital stock construction enables it to measure relatively high-level skills in the technology-oriented research as well. The inference that engineering-technical skills (B.S. level) are of high value is not warranted. These results are complementary with the Indian study results referred to earlier. Though based on different data, the implied appropriated streams in this study are close to those estimated for India. In the developing countries a considerable amount of transfer of benefits based on knowledge diffusion takes place. Part 3 of the calculation shows, however, that such transfer depends heavily on the capacity of indigenous research. The strategy of waiting for the neighbor's technology to "spill in" just doesn't work. The country without an indigenous research capability benefits very little from its neighbor, even when the neighbor is considerate enough to invest in research.

The levels of the income streams are extraordinarily high and imply returns to research investment several times higher than those realized on normal investment. The research dollar buys income streams many times as large as the average development dollar, though given the time-lags the price of growth through research investment is probably one-fifth to one-eighth as high as it is in most development projects.

An Ad Hoc Computation of Returns to International Center Research in Wheat and Rice

The computation of returns to investment in international center research cannot be made without first making some rather arbitrary assumptions. Were it not for the tremendous importance for policy of such a calculation, it probably should be avoided. The procedure utilized here starts with the reasonably solid information summarized in Table 9-2. These estimates of the economic value of wheat and rice which would *not* have been produced if none of the HYV's had been discovered is based on the regression analysis in Table 9-6. This, of course, is most certainly *not* an estimate of the contribution of CIMMYT and IRRI. In fact, the crude allocation of varieties by center, joint center-national, and independently produced varieties suggests that in the absence of CIMMYT and IRRI some HYV's would have been produced.[9] It is even likely that a large number of HYV's might have been produced eventually, since the independently developed varieties have been adopted at a significant rate in comparison with IRRI and CIMMYT varieties.

Table 9-2. Benefit Streams Associated with High-Yielding Varieties in Asia and North Africa

Benefit Streams	1965-66	1966-67	1967-68	1968-69	1969-70	1970-71	1971-72	1972-73
			Wheat					
Aggregate adoption level of all HYV's (%)	.001	1.5	9.7	18.9	20.5	24.0	28.3	34.1
Proportions owing to								
CIMMYT-bred varieties	.001	1.5	8.8	16.6	17.0	18.7	20.4	23.0
Joint CIMMYT-national	0	0	.8	1.9	2.5	3.6	5.6	7.5
Other independent	0	0	.1	.5	1.0	1.7	2.3	3.6
Value[a]								
at $75 per metric ton (million dollars)	.03	30	170	325	340	403	445	523
at $130 per metric ton (million dollars)	.04	52	293	563	590	697	772	906
			Rice					
Aggregate adoption level of all HYV's (%)	.001	1.1	3.4	6.0	9.9	13.1	17.1	20.9
Proportions owing to								
IRRI varieties	.001	1.0	2.9	4.6	7.0	9.1	10.5	13.3
Joint IRRI-national	0	0	0	.4	.9	1.4	3.2	3.4
Other independent	0	.1	.1	1.0	2.0	2.6	3.4	4.2
Value[a]								
at $100 per metric ton (million dollars)	.07	76	233	420	695	905	1155	1359
at $175 per metric ton (million dollars)	.11	133	407	736	1216	1584	2022	2379

[a] In computing these benefit streams, the following geographic groupings were utilized: *Wheat*. Production from all developing countries plus the Southern European countries. *Rice*. Production of rice from all tropical and semitropical developing countries, excluding South Korea and Taiwan.

The lower prices are representative of those in the 1970-72 period; the higher prices are more representative of 1975.

These figures differ somewhat from the author's earlier computations reported in "Consequences of the Green Revolution," Economic Growth Center, Yale University, 1974 (mimeographed). The major differences are attributable to the use of geometric rather than arithmetic means in the computations, different geographic groupings, and somewhat more accurate production data. The results reported here are more consistent with Dalrymple's estimates than were the earlier figures; for comparisons see chapter 7.

Table 9-3. Income Stream and Cost Calculation for International Center Research

Item	First Generation Varieties (1966/67-1969/70)		Second Generation Varieties (1970/71-1972/73)	
	Wheat	Rice	Wheat	Rice
Annual increment to income stream (1973 million dollars)[a]	182	142	74	301
Associated cost on annual basis (1973 million dollars)[b]	.6	1.0	1.2	2.8
Income stream per $1,000 investment	$303,000	$142,000	$62,000	$108,000

[a] Computed from Table 9-2 utilizing prices of $130 per metric ton for wheat and $175 per metric ton for rice.

[b] Computed from Dalrymple, chapter 7. The second generation costs are based on IRRI and CIMMYT Annual Budgets. That is, it is supposed that the research program during these years was primarily responsible for the production gained during the second generation period. First generation costs are all prior costs at IRRI (capital expenditures are amortized), and a capital adjustment is made for CIMMYT costs to make them roughly comparable with IRRI costs.

One could attempt to estimate this alternative pattern of varietal development to determine how much should be attributed to the centers, but this would be very difficult. It would also bias the result against the centers, since the development of the independent varieties is not truly independent. Instead, a computation which is something of an overestimate will be made. First we compute income streams to each center based on the center varieties plus one-half the center-national joint varieties. These are averaged for the first five years of the adoption pattern and for the last three years. These can be taken to represent the income streams associated with the first and second generations of center varieties. Then, if the cost data can be matched up with these benefit streams, an estimate of the income stream associated with an investment of $1,000 is possible. Table 9-3 summarizes this calculation.

The results of this calculation show, not surprisingly, that the income streams purchased by investing in both the CIMMYT and the IRRI programs have been truly extraordinary. The Mexican wheats, when introduced in India and Pakistan, were quickly adopted in the regions to which they were suited. The IRRI-type rice, on the other hand, was adopted at a slower pace and required more systematic screening and the adaptation of complementary technologies. This is reflected in the calculated income streams. The distinction between first and second generation varieties is somewhat arbitrary and is designed primarily to show marginal gains to the extent possible. The CIMMYT

income stream in the first generations of varieties going into India is extremely high but drops considerably in the second generation time period because new adoption has slowed down. The IRRI-generated stream declines only moderately, as adoption of the varieties in the second period was almost as great as in the first period. The second generation income streams, while still far above income streams consistent with efficient investment, do not greatly exceed those indicated for national system investment.

It should be noted, however, that both the national system and the international center computations are subject to error and are not strictly comparable in terms of the timing of benefits. In addition, these computations are based on the results of relatively new research programs. As these programs mature and expand it is highly improbable that benefit streams of the order measured here could be attained. Thus it would not be realistic to expect these high returns to continue to be realized as the international system expands and as national system investment is increased.

Policy Implications of Agricultural Research Productivity

The estimated income streams associated with investment in virtually all types of research programs from a large number of studies must be taken as evidence that investment levels are less than optimal. The computed rates of returns are well above the social opportunity cost of investable funds. If one considers the available evidence regarding the payoff to investment in the full range of development projects undertaken in the low-income countries, it simply is not possible to match the returns realized to research investment. Still we find that research system development does not have high priority in the programs of many developing countries. And international funding has given it low priority as well.

A recent study by Boyce and Evenson[10] provides new data on the willingness of countries to invest in agricultural research and extension. Table 9-4 summarizes investment in agricultural research and extension in constant (1971) United States dollars by major regions of the world. The research data include private industrial sector research and agriculturally related scientific research. The extension data do not include private sector extension activity.

The research data also include international center investment which in 1974 totaled some $30 million, less than 5 percent of low-income country investment. The study in question estimated that total international aid agency funding of low-income country research in the 1950s was on the order of $50 million per year, representing 40 to 50 percent of total investment. By 1965, aid funding had risen to roughly $100 million per year and still accounted for roughly one-third of national system investment in the low-income coun-

Table 9-4. Expenditures for Agricultural Research and Extension by Major World Regions, 1951-74

Region	1951	1959	1965	1971	1974
	Total Annual Expenditures for Research (millions of 1971 constant U.S. dollars)				
Western Europe	130.0	172.3	407.4	671.0	733.4
Eastern Europe and USSR	132.2	365.2	626.8	818.0	860.5
North America and Oceania	365.7	540.0	805.9	1203.4	1289.4
Latin America	29.7	39.2	73.0	146.4	170.3
Africa	41.3	58.0	113.5	138.5	141.1
Asia	70.0	131.0	356.4	610.2	646.0
World Total	768.9	1305.7	2383.0	3587.5	3840.7
	Proportion of Total Annual Expenditures for Research Accounted for by Industrial Sector Research (%)				
Western Europe	12.6	12.4	11.7	10.8	10.8
Eastern Europe and USSR	7.5	7.4	8.1	8.3	8.3
North America and Oceania	28.0	28.3	26.9	24.9	25.4
Latin America	3.3	3.6	3.6	3.2	5.1
Africa	2.9	3.5	3.5	2.9	2.9
Asia	2.8	2.5	2.4	2.2	2.2
World Total	17.4	15.9	13.9	12.9	13.1
	Proportion of Total Annual Expenditures for Research Accounted for by "Agriculturally Related" Scientific Research (%)				
Western Europe	19.8	19.5	24.8	27.6	27.6
Eastern Europe and USSR	27.0	26.4	19.0	17.2	17.2
North America and Oceania	11.7	11.7	12.2	16.3	16.4
Latin America	9.2	9.2	11.5	14.1	14.0
Africa	6.7	5.8	6.9	9.2	9.2
Asia	19.8	18.9	23.3	25.9	25.9
World Total	11.3	17.2	13.3	19.9	20.5
	Total Annual Expenditures for Extension (millions of 1971 constant U.S. dollars)				
Western Europe	n.a.	99.4	169.5	196.6	183.3
Eastern Europe and USSR	n.a.	128.0	90.0	230.0	250.0
North America and Oceania	n.a.	163.1	198.4	263.5	287.6
Latin America	n.a.	32.4	51.1	102.8	121.9
Africa	n.a.	90.7	161.0	217.0	224.5
Asia	n.a.	73.2	160.0	249.5	258.5
World Total	n.a.	586.8	930.0	1259.4	1325.8

Source: James K. Boyce and Robert E. Evenson, *National and International Agricultural Research and Extension Programs* (New York: Agricultural Development Council, Inc., 1975).

Table 9-5. World Expenditures on Research and Extension as Percentages of the Value of Total Agricultural Product by Annual Per Capita Income Group, 1951-74

Income Group (1971 U.S. dollars)	1951	1959	1965	1971	1974
			Agricultural Research		
Over $1,750	1.21	1.26	1.80	2.48	2.55
$1,000-1,750	.83	1.19	1.95	2.34	2.34
$400-1,000	.40	.57	.85	1.13	1.16
$150-400	.36	.37	.62	.84	1.01
Under $150	.22	.28	.47	.70	.67
			Agricultural Extension		
Over $1,750	n.a.	.45	.52	.61	.60
$1,000-1,750[a]	n.a.	.17	.22	.33	.31
$400-1,000[a]	n.a.	.26	.40	.46	.40
$150-400	n.a.	.67	.99	1.44	1.59
Under $150	n.a.	.57	1.04	1.76	1.82

Source: James K. Boyce and Robert E. Evenson, *National and International Agricultural Research Extension Programs*. New York: Agricultural Development Council Inc., 1975).

[a] Excluding Eastern European countries.

tries. After 1965, international aid to national research systems declined to the $60 to $70 million level by 1971. Some increase may have taken place since 1971.

Table 9-5 summarizes the data in Table 9-4 by grouping countries by per capita income level (as of 1971). Here we can see a rather extraordinary correlation between level of development and the propensity to invest in research and extension. The low-income countries have clearly opted to expand extension systems. (It should be noted, however, that the lack of private sector extension activity, which would be more heavily concentrated in the high-income countries, biases this picture.) The research data indicate that from 1965 to 1971 low-income countries did expand research system investment even though international funding was declining during this period. The 1974 data, on the other hand, show little further increase except in the $150-400 per capita income group. This lack of progress is very likely to have serious future consequences.

There are several economic explanations for the relatively high estimated rates of return to research investment. The supply of research skills in the developing countries may be such that the real marginal cost of skills from a social perspective is above the average cost of the skills. (In fact, most of the high-level skills have been created with fellowship support from international agencies. The expected returns to fellowship investment are presumed not to

be fully captured by the fellowship recipient. The computed rates of return then do not fully account for the actual investment.)

Externalities associated with the diffusion of technology are probably an important factor in holding down investment levels. The proposition that technology is relatively easily transferred through investment in extension activities has been stressed in a great deal of the development literature. Countries have been led to believe that much of their own investment will produce benefits which they will not be able to appropriate. Conversely, with a little investment in extension they have expected to appropriate the results of other research programs. The studies reported in this chapter indicate that this policy strategy has not paid off. The degree of diffusibility of technology has been much lower than supposed. Countries without an indigenous research capability have benefited little from research in other countries. Had these countries' judgment been correct, the expected rates of return to the appropriated income streams from research would have been normal, but the returns computed from the full income streams would be above normal.

National systems may be discounting the expected income streams to take into account possible social costs associated with factor adjustment. These have not been considered in the studies reported here. Two recent studies of the determinants of research investment provide evidence that countries which produce higher proportions of both exported and imported commodities do invest more in agricultural research.[11] Since these commodities have relatively high demand elasticities, realized technology change will create fewer adjustment pressures.

Finally, *ex-post* measures cannot automatically be taken to reflect *ex-ante* expectations. This is especially serious when research programs are obvious successes in an *ex-post* sense. The extraordinarily high rates of returns to investment in CIMMYT and IRRI probably could not have been expected in advance. On the other hand, those studies which include the entire spectrum of research on a commodity or commodity group, such as the cereal grains study, are not subject to serious bias on this score.

Several additional factors have probably also been important in guiding research investment policy in both national and international systems. Not the least of these is the high level of administrative skill demanded in the stronger research institutions. Extension and rural development projects are much easier to organize and administer than are effective research programs. A second major factor is the persistent preference for quick results in development projects.

The prognosis for future productivity advances in the developing countries is mixed. On the one hand, while national system investment is well below optimum, significant progress has been made, at least until 1970. The im-

provement in many national systems in recent years should lead to improved agricultural performance in the late 1970s. But only a few countries have really given research system development a major place in development plans. For much of the developing world, investment in the expansion of research capacity is so low that the prospects for rapid technology improvement are dim.

The further development and expansion of the international centers system, although probably having a high expected payoff, do not really hold promise for many of these regions. It simply is not practically possible for a single research organization to produce technology which will be relevant to more than a small fraction of the world's producers. Consequently, the impact of the international centers ultimately depends on the existence of strong national systems. The international centers have demonstrated that they can be tremendously productive in a setting of weak national systems. As strong national systems are developed, their role will change and they will have to move toward a greater emphasis on their comparative advantage in more basic science research.

APPENDIX

Appendix 9-1. Cereal Grains Productivity Analysis

The basic specification actually utilized in the cereal grains productivity analysis was

$$P = CL^{a_1} F^{a_2} TR^{(a_3 + a_4 SR)} RTR^{(a_5 + a_6 ZSR + a_7(TR + SR) + a_8(TR + SR)^2)} RP^{(a_9 + a_{10} TR)}$$

where

P, L, and F are measures of production, land, and fertilizer use in quantity units for each country. Each is expressed relative to the average 1948-50 base level of the variable. Thus the analysis is of changes in productivity relative to the base period.

TR and SR are knowledge capital stocks in each country. TR measures technology-oriented research capital, and SR measures science-oriented research capital. Again, a price must be paid for this specification in that the only possible measure of research activity by orientation in international data is by publications. A direct measure of scientist man-years or expenditures would be preferable. Fortunately, we have available internationally consistent data on publications oriented to specific cereal grains from *Plant Breeding*

Abstracts. The cumulated sum of the publications for each cereal grain with a distributed lag forms the TR variable.

$$TR(t) = \sum_{t=1942}^{t-5} P_t + .8P_{t-4} + .6P_{t-3} + P_{t-2} + .2P_{t-1}.$$

With a three-year lag from investment to publication the formulation implies an eight-year lag until research becomes fully productive.[12] The SR variable is constructed in a similar manner from publications data in scientifically oriented publications in the fields of plant physiology, phytopathology, and soil science abstracted in *Biological Abstracts*.

RTR and ZSR are the counterpart "borrowable" research capital stocks available from ecological neighbors. Ecological neighbors are defined as being in the same geoclimate *region* in the case of RTR or the same geoclimate *zone* in the case of ZSR. The geoclimate regions and zones are adapted from the work of Papadakis.[13] The specification is designed such that the science stock does not directly contribute to productivity. Its contribution comes through improving the productivity of the technology-oriented knowledge stock. The terms (TR + SR) and $(TR + SR)^2$ in the exponent of RTR measure the degree of complementarity or substitutability of indigenous research-based knowledge to the borrowable stocks.

The term RP is an index of productivity change in cereal grain production in ecologically neighboring countries. It is, of course, itself a function of research capital stocks, but it measures actual realized technical change. It reflects some random elements as well as development and adoption investment and is designed to distinguish between direct technology transfer and knowledge transfer. When a country is in more than one geoclimate zone (as most are), the allocation to each zone for purposes of the definition of RTR, RP, and ZSR is proportional to the crop production area. In addition, research variables are "deflated" by the number of geoclimate regions in the country (adjusted for the size of regions).[14]

The results of regression analysis of this model were carried out for three alternative sets of cereal grains data reported in Table 9-6.

The reported regressions were estimates which utilized the Nerlove-Baelestra procedure for modified generalized least-squares estimates with combined time-series cross-sectional data. The principal features of the first two regressions are the following:

1. The land coefficients are approximately what would be expected if land serves as a proxy for the "left-out" variables, labor and power. This is not the only interpretation possible, but it suggests that the problem of missing data is not too serious. The fertilizer coefficients are reasonable.

Table 9-6. Sources of Variation in the Index of Cereals Grain Production[a]

	Independent Variable	Developed Countries[b] Regression (1)	Developing Countries[c] Regression (2)	Developing Countries[c] Regression (3)
a_1	Land	.965	1.011	1.083
	[LN(Land)]	(199.8)	(288.7)	(222.9)
a_2	Fertilizer	.0333	.0318	.0273
	[LN(Fert)]	(8.67)	(6.26)	(5.38)
a_3	Country T research	.00707	.00231	.0021
	[LN(TR)]	(2.09)	(.75)	(.70)
a_4	Country T x country S research	.00000404	.0000684	.0000524
	[LN(TR)*SR]	(1.64)	(7.33)	(5.44)
a_5	Regional T research	.01611	− .00014	− .00231
	[LN(RTR)]	(2.46)	(.05)	(.71)
a_6	Regional T x zonal S research	.0000639	.000147	.000157
	[LN(RTR)*ZSR]	(12.09)	(10.56)	(11.40)
a_7	Regional T x country T + S research	.0000093	.000095	.00010
	[LN(RTR)*(TR + SR)]	(2.81)	(5.17)	(5.18)
a_8	Regional T x country T + S research squared	.00000000023	− .000000045	− .000000065
	[LN(RTR)*(TR + SR)^2]	(1.46)	(16.06)	(7.49)
a_9	Regional yield index	.1753	.0627	.0026
	[LN(RY)]	(5.38)	(2.26)	(.09)
a_{10}	Regional yield x country T research	− .000215	− .00061	− .00036
	[LN (RY)*TR]	(10.12)	(8.94)	(5.07)
a_{11}	Percentage area planted to high-yielding varieties			.00574
	[HYV]			(2.93)
a_{12}	HYV percentage squared			− .00154
	[(HYV)^2]			(3.67)
a_{13}	HYV percentage x country T research			.0000144
	[HYV*TR]			(5.81)
a_{14}	Dummy for wheat	− .2233	− .018	− .060
		(10.47)	(1.53)	(4.67)
a_{15}	Dummy for barley	− .2777	− .081	− .094
		(14.29)	(4.69)	(5.46)
a_{16}	Dummy for rice	− .3455	− .097	− .1164
		(12.57)	(7.29)	(8.81)
Constant		.565	.026	.087
		(10.55)	(.51)	(2.06)
R^2 (Adj.)		.981	.986	.987

[a] Regressions weighted by area and estimated using Nerlove-Baelestra techniques; t ratios in parentheses.
[b] Eighty-seven crop-country combinations, 1948 to 1971 (2,088 observations).
[c] Seventy-eight crop-country combinations, 1948 to 1971 (1,872 observations).

Table 9-7. Wheat and Rice Production: A Simplistic Regression Model

Independent Variable[a]	Wheat Production[b]	Rice Production[c]
Land	.9836	1.0374
[LN(Land)][d]	(.0030)	(.0030)
Fertilizer	.0411	.0477
[LN(Fert)][d]	(.0058)	(.0021)
Percentage area planted to high-yielding varieties	.0430	.0052
[HYV][e]	(.0018)	(.0010)
HYV percentage squared	− .00085	− .00005
[(HYV)^2]	(.00004)	(.00002)
Constant	.1758	− .2208
R^2	.9859	.9965

[a] Dependent variable is LN(Production). Production is scaled relative to average levels in 1948-1950.

[b] In thirteen Asian and Middle Eastern countries, 1948 to 1971 (307 observations); regressions weighted by area harvested; standard errors in parentheses.

[c] In twelve Asian and Middle Eastern countries, 1948 to 1971 (282 observations); regressions weighted by area harvested; standard errors in parentheses.

[d] Land and fertilizer are scaled relative to average levels in 1948-1950.

[e] HYV is the percentage of the acreage of wheat or rice planted to high-yielding varieties as defined by Dana G. Dalrymple, *Development and Spread of High-Yielding Varieties in the Less Developed Countries*, Foreign Agricultural Economic Research Report no. 95 (Washington, D.C.: Economic Research Service, USDA, 1974).

2. Indigenous technological research (TR) is primarily productive when interacting with scientific research (SR). The a_4 coefficient is highly significant in all but the developed-country regions. Note that the productivity of TR depends on both a_3 and a_5. A negative a_3 (as in the rice regression) does not mean that TR is unproductive. Its net contribution is positive.

3. Research by ecological neighbors is of value as indicated by the a_6 and a_7 coefficients. Again the productivity is primarily in the form of interactions. The (TR + SR) terms indicate that indigenous research *complements* the borrowable research at low levels but *substitutes* for it at high levels.

4. The RP variable indicates that indigenous research is less productive when the rate of productivity in ecologically neighboring countries is higher. Technically this is the case, holding constant the research capital stocks in the neighboring countries. Thus it bears the interpretation that the more efficient neighboring countries are in converting research capital into productivity the more likely it is that the resultant technology or technical knowledge will be transferred.

Regression (3) in Table 9-6 is based on an extension of the model to incorporate the extraordinary productivity gains associated with the international institutes. The variable HYV is measured as the percentage of wheat (or rice) area planted to high-yielding varieties as defined by Dalrymple.[15] The results

Table 9-8. Regression Analysis: Wheat and Rice Production in Asian and Middle Eastern Countries, 1948-71[a]

Independent Variable	Wheat Production[b]	Rice Production[c]
Land	1.0050	1.0217
[LN(Land)]	(63.5)	(107.4)
Fertilizer	.0693	.0409
[LN(Fert)]	(4.05)	(2.91)
Country T research	.0112	− .0144
[LN(TR)]	(1.10)	(2.54)
Country T x country S research	.00067	.00024
[LN(TR)*SR]	(4.36)	(2.00)
Regional T research	.1656	− .0179
[LN(RTR)]	(6.16)	(2.08)
Regional T x zonal S research	.000046	.000010
[LN(RTR)*ZSR]	(2.29)	(1.52)
Regional T x country T + S research	− .00068	.00002
[LN(RTR)*(TR + SR)]	(2.39)	(.18)
Regional T x country T + S research squared	− .00000074	− .00000018
[LN(RTR)*(TR + SR)^2]	(4.35)	(6.00)
Percentage area planted to high-yielding varieties	− .002569	− .0097
[HYV]	(.61)	(1.96)
HYV percentage squared	− .0000716	− .000018
[(HYV)^2]	(.86)	(.27)
HYV percentage x country T research	.0089	.000039
[HYV*TR]	(3.63)	(5.70)
Time	.296	− .0181
[LN(Time)]	(2.33)	(3.63)
Constant	− 2.47	1.22
R^2 (Adj.)	.987	.998

[a] Regressions weighted by area and estimated utilizing Nerlove-Baelestra techniques; t ratios in parentheses.
[b] In ten Asian and Middle Eastern countries (240 observations).
[c] In twelve Asian and Middle Eastern countries (120 observations).

in regression (3), Table 9-6, show that as the percentage planted to HYV's increases the contribution to production decreases (the negative HYV^2 term). They also clearly show that the contribution of HYV's depends on the indigenous research capital stock. Table 9-7 is basically intended to show how misleading a simplistic approach to the green revolution can be when the HYV variables are postulated to be the only determinants of productivity change in the regressions reported there. The HYV category includes varieties developed directly by CIMMYT or IRRI, varieties developed by national systems utilizing CIMMYT or IRRI genetic material, and varieties developed independently of the international centers (e.g., the ADT-27, Mahsuri, TN-1, C4-63, and related rice varieties, Bezostaya [a Russian wheat variety], and other Iranian, Tunisian, and Italian varieties).

These regressions are based only on the wheat and rice data. They indicate that the productive contribution declines to zero at 26 percent adoption for wheat and 52 percent adoption for rice. This of course is to be expected if the HYV mix is a fixed set of varieties. The productive effect will be highest in the areas of earliest adoption and will be exhausted as the acreage expands in geoclimate conditions less suited to the varieties. But Dalrymple's HYV measure is a changing indicator of technology. In particular, it includes varieties produced by national systems.

Table 9-8 presents regression results based on wheat and rice data when research capital is incorporated into the specifications. Note that the interaction with indigenous research, TR, is the important variable, as it was in the regressions based on data from all cereal grains. The diminution of the productivity of HYV's is maintained in the Table 9-8 regressions, if TR is held constant. At high levels of TR, however, the scope of the coverage of HYV's will be much greater than 25 to 50 percent before the productive effect is exhausted.

NOTES

1. Robert E. Evenson and Yoav Kislev, "Investment in Agricultural Research and Extension: A Survey of International Data," *Economic Development and Cultural Change*, 23 (April 1975), 507-521.

2. Comments by Webster and Ulbricht at the Airlie House conference reflected appropriate skepticism toward some of the cruder estimates.

3. Yujiro Hayami and Vernon W. Ruttan, *Agricultural Development: An International Perspective* (Baltimore and London: Johns Hopkins Press, 1971).

4. Robert E. Evenson and Yoav Kislev, *Agricultural Research and Productivity* (New Haven: Yale University Press, 1975), chapter 5.

5. Robert E. Evenson and Yoav Kislev, "Research and Productivity in Wheat and Maize," *Journal of Political Economy*, 81 (September-October 1973), 1309-1329.

6. For a more complete discussion of this study see Robert E. Evenson and Dayanath Jha, "The Contribution of Agricultural Research Systems to Agricultural Production in India," *Indian Journal of Agricultural Economics*, 28 (October-December 1973), 212-230.

7. Rakesh Mohan and Robert E. Evenson, "The Intensive Agricultural Districts Program in India: A New Evaluation," *Journal of Development Studies*, 11 (April 1975), 150.

8. Robert E. Evenson, "The Green Revolution in Recent Development Experience," *American Journal of Agricultural Economics*, 56:2 (May 1974), 387-394.

9. Based on footnotes from Dana G. Dalrymple, *Development and Spread of High-Yielding Varieties in the Less Developed Countries*, Foreign Agricultural Economic Research Report no. 95 (Washington, D.C.: Economic Research Service, USDA, 1974).

10. James K. Boyce and Robert E. Evenson, *National and International Agricultural Research and Extension Systems* (New York: Agricultural Development Council, Inc., 1975).

11. Evenson and Kislev, "Research and Productivity in Wheat and Maize," "Investment in Agricultural Research."

12. The eight- to ten-year time-lag is approximately the lag estimated for the United States. Robert E. Evenson, "Economic Aspects of the Organization of Agricultural Research," *Resource Allocation in Agricultural Research*, ed. W. L. Fishel (Minneapolis: University of Minnesota Press, 1971).

13. Juan Papadakis, *Climates of the World and their Agricultural Potentialities* (Buenos Aires: privately printed, 1966).

14. See Evenson and Kislev, *Agricultural Research and Productivity*, for the adjustment rationale.

15. Dalrymple, *High-Yielding Varieties*.

10

A Model of Agricultural Research[1]

Yoav Kislev

There is substantial evidence to support the notion that the rate and direction of agricultural research are influenced by economic circumstances.[2] The issues involved in this proposition are usually discussed in terms of "demand-oriented research" or "biased technological change" and focus on the payoffs to potential innovations.[3] However, as is so often the case, equilibrium is determined by both demand and supply. The basic building block of the theory of supply is the theory of production. The purpose of this chapter is to suggest a formal model of research, particularly of applied research, in the hope that this model will contribute a theory of the production of knowledge and help in understanding the supply side of the process of technical change.

The most important difference between the production of knowledge and the production of tangible goods is the strong element of uncertainty associated with the outcome of research work, and it is on this element that the present model focuses. The model is inspired by Stigler's work on the economics of information and is similar in some aspects to Nelson's treatment of research and development.[4]

The discussion starts with a presentation of an actual example. Applied research is modeled as a search in a distribution of unknown outcomes. One section discusses the properties of the model, and another is devoted to the effect of advancement in basic knowledge on applied research.[5] The last section draws some implications for the problems of the international agricul-

tural research centers and highlights a severe shortcoming in our understanding of the operation of research systems, particularly publicly supported systems.

The Development of Modern Sugarcane Varieties

To create the model, it will be useful to open our discussion with a short history of sugarcane variety development (see also chapter 8).

Four stages can be identified in the history of sugarcane breeding. First, sexual reproduction of the cane plant was not known, and as a result, improvements in the plant were very slow to come, based on occasional and rare cases of "natural" sexual reproduction. The second stage can be dated from 1887, when it was discovered that proper light and temperature conditions can induce flowering and thus sexual reproduction. Crossings were then made and offspring observed, and seedlings with superior potentials were selected and propagated vegetatively. At this stage, crossing was random. The major innovation of the third stage was the directed crossing of selected parents, aimed at specifically influencing characteristics of offspring. At this stage, wild, disease-resistant cane varieties were introduced into the breeding program. The fourth stage marks the modern period in sugarcane breeding wherein most of the effort has gone into the development of species suited to specific local climate and technology conditions.

Starting with the second, each stage was characterized by an innovation in the method of research. This innovation augmented significantly the productivity of research, which in turn encouraged the establishment of new experiment stations and the development of new varieties. After a while, however, returns to research began visibly to diminish, as the potentials revealed by the innovation were gradually exhausted.

In statistical terms, each crossing is a random drawing from the population of all genetically possible types. This selection is a process of search, by drawing, in a population of outcomes. Figure 10-1 depicts the four stages of sugarcane development. In the first stage virtually all the observations – cane plants in the field – were concentrated around one value with very little probability of discovering different types. In Stage 2 the *sample variance* was increased tremendously; both inferior and superior types were observed among the seedlings, and the best were selected. By identifying parents, search in the third stage was limited mostly to one portion of the population. That portion is in itself a new population centered around a higher mean than those of the original Stage 1 and Stage 2 populations. Similarly, Stage 4 marks a shift to a new, different population.

The selection depicted in Figure 10-1 is unidirectional, aimed, say, at achiev-

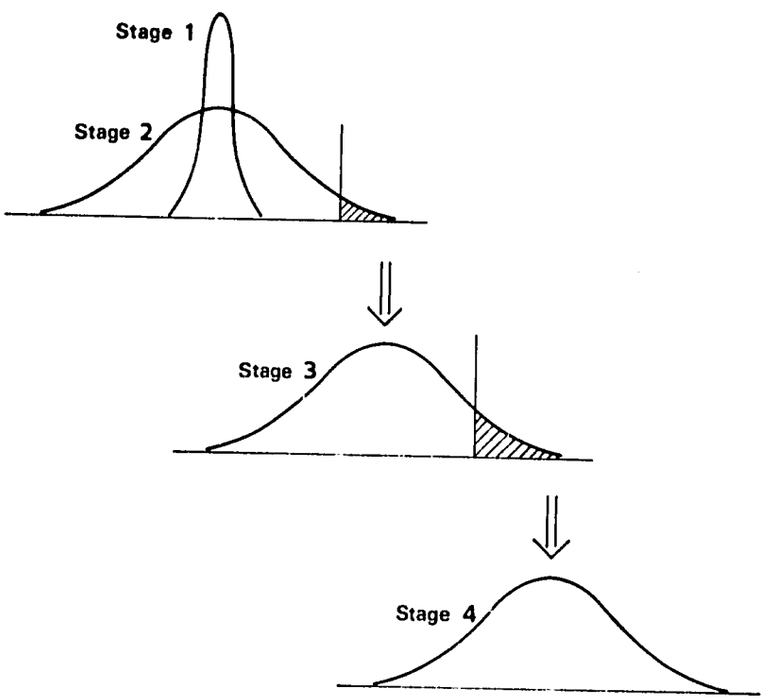

Figure 10-1. Stages in the development of sugarcane varieties.

ing higher yields. In reality, selection processes usually cover more than one characteristic of the organism. For simplicity, at this stage, the model to be developed below is also limited to unidirectional selection processes.

For concreteness, our discussion will be couched in terms of genetic-selection application and yields, but the model is of wider application. Research in other areas, such as organic chemistry, pharmacology, and the development of plant protection compounds, is technically a search and selection process, similar to breeding processes.

The Model

Imagine a scientist (or a scientific team) working to improve technology to increase the yield of a crop. To simplify, let us assume that income is proportional to yield and that the objective of the scientist is to maximize income of the whole system – research and production. Here, of course, is hidden one

of the crucial issues of applied research: What signals does the research system get from its "customers," and what dictates its response? We simply assume that the scientist is aware of the economic implications of his work and acts to maximize net benefits. The scientist faces a given distribution of genetic types, which he searches to find the best. An experiment is, in our formulation, a sample drawn from the distribution of unknown outcomes. In each period the scientist conducts such an experiment, that is, he draws one sample. The genetic types obtained in the sample are ordered by their yield level, the highest yield regarded as the outcome of that experiment. If the outcome of the experiment is better than the currently practiced technology (variety), the newly discovered technology will replace the old and yield (income) will rise. If not, the current variety is maintained. Experimentation may then continue.

The process is illustrated with the exponential distribution which can be taken to approximate the right-hand tail of the normal distribution. The exponential distribution is $f(x) = \lambda e^{-\lambda(x-\theta)}$ and it can be shown that for large samples the distributions of the maxima (which is what we are interested in here) converge to the same distribution for a large class of original distributions including the normal and the exponential.[6] In Figure 10-2 yield is measured along the horizontal axis, cumulative probability and probability density along the vertical axes. The experiment depicted in the figure is composed of a sample of three drawings from the random exponential distributions – with yields x_1, x_2, x_3. In the figure x_3 exceeds the current yield level, marked y; therefore a variety replacement will take place, yield increment being Δy – the difference $x_3 - y$. Had the yield of the best variety in the experiment been smaller than y, the use of the current variety (with yield y) would have continued.

Since the actual outcome of the experiment is not known in advance, the value of the *expected* contribution, $E(\Delta y)$, for a given distribution of potential outcomes depends on the following two magnitudes.

1. The extent of experimentation, that is, the number of observations. The larger this number, the higher the probability of finding x values of larger magnitude. The probabilities, the density functions for the highest value in a sample, are depicted for five values of n in Figure 10-3.

2. The value of y – the current yield level. The higher the current level of technology, the less probable it is that an improvement will be discovered.

The economic value of the expected technological improvement is the present value of its future contributions. For simplicity of exposition we shall regard it here as $1/r[E(\Delta y)]$. This will be the correct contribution if experimentation is to take place only once; if it continues in later periods, an improvement today "spoils" the chances of improving technology tomorrow. This

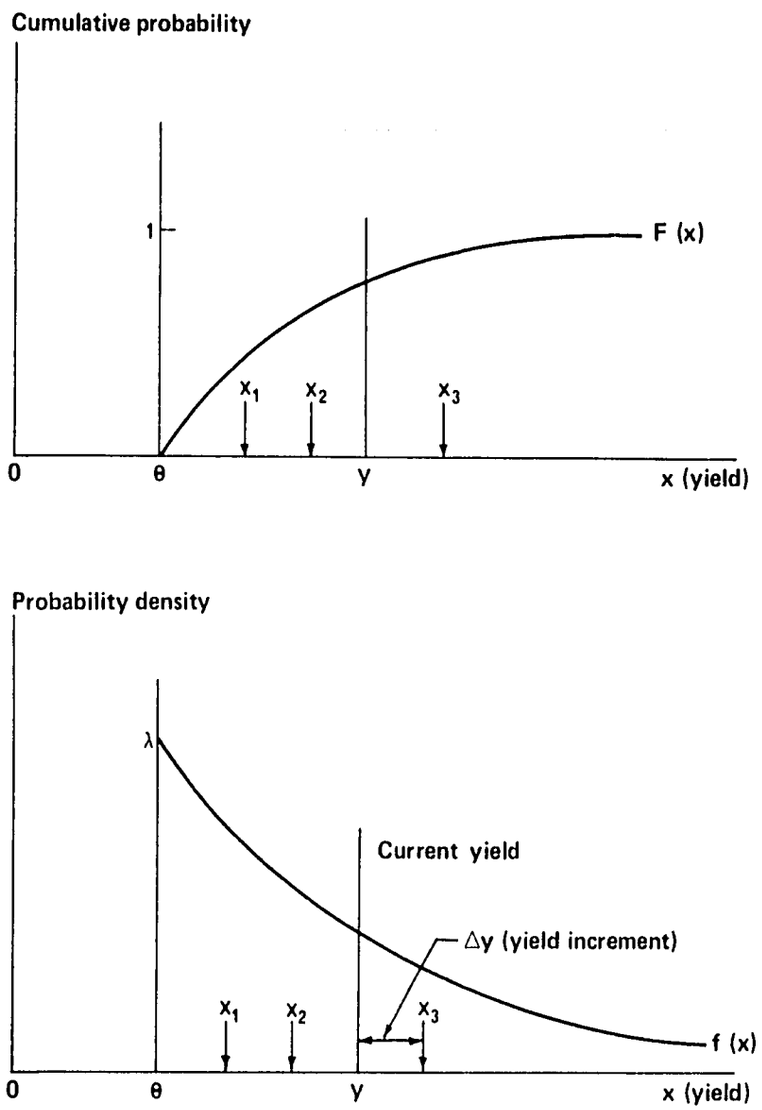

Figure 10-2. The exponential distribution with a sample of three observations.

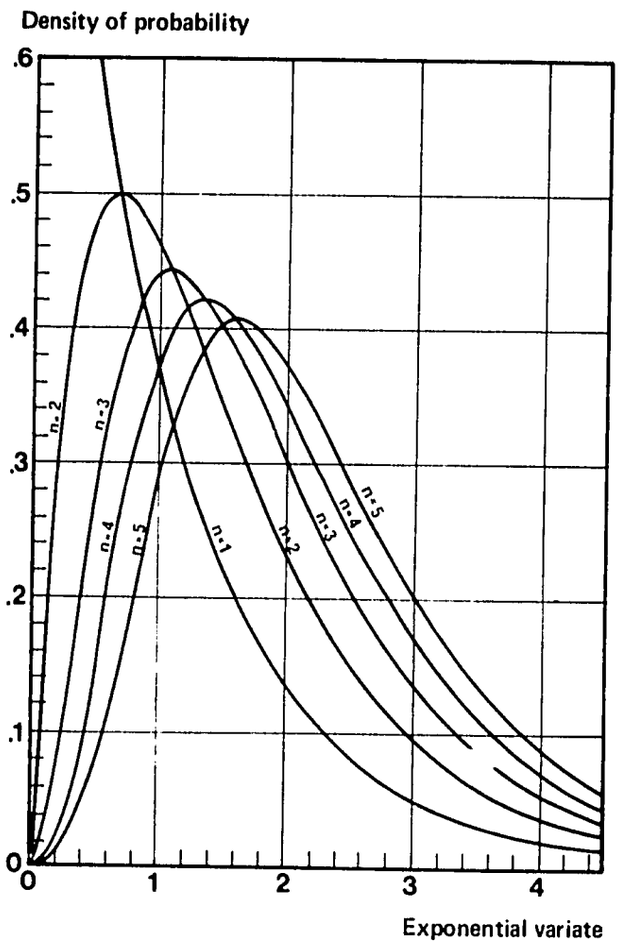

Figure 10-3. Density functions for maximal values of the exponential distribution $f(x) = e^{-x}$ for $n = 1, \ldots, 5$.
Source: E. J. Gumbel, *Statistics of Extremes* (New York: Columbia University Press, 1958), by permission of publisher.

means that for an ongoing research project the economic value of the expected technological improvement is lower than $1/r[E(\Delta y)]$, but this does not affect the relevant properties of the research system to be analyzed below.

The economic problem of the research system is to decide on the optimal amount of experimentation to conduct in each period – on the optimal num-

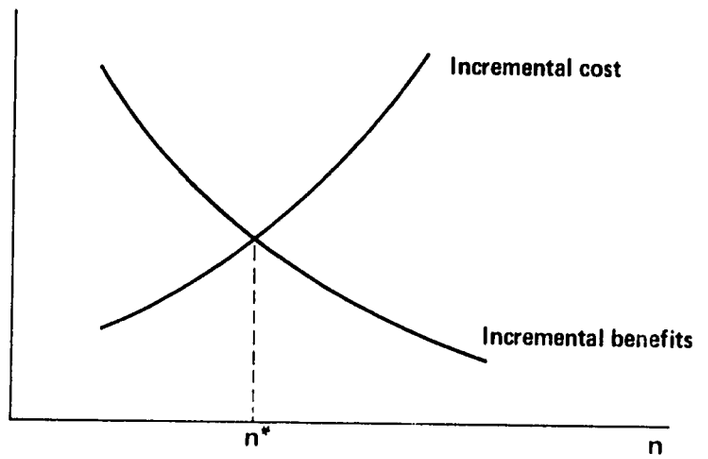

Figure 10-4. Optimal number of observations, n* (the smooth graphs in the diagram approximate step functions).

ber of observations, n, to draw. A reasonable assumption is that cost of research is an increasing function of n. Average costs may decrease for small values of n. This introduces nonconvexities which are assumed away at this stage. As an examination of Figure 10-3 will reveal, incremental technology improvement is a decreasing function of the number of observations; that is, each additional observation adds something to the expected technology increment, $E(\Delta y)$, but these additions get smaller and smaller as the number of observations increases. The magnitude $E_n(\Delta y) - E_{n-1}(\Delta y)$ is positive and decreasing with n. We get, therefore, the familiar equilibrium position determined by the intersection of marginal (incremental) cost and returns (see Figure 10-4).

Implications and Extensions

Technological research is more fruitful the wider the divergency between the level of theoretical scientific knowledge and the level of technology in practice. Nelson and Phelps made this assumption in their model of technological diffusion and schooling.[7] Evenson and I estimated the increase in the productivity of research in one country owing to the availability of relevant knowledge in other countries.[8] Technological gaps also explain rates of international technology diffusion when adaptive-type applied research is needed to facilitate the transfer of knowledge (see chapter 8).

In our framework a formal definition of the *technological gap* is the differ-

ence $y - \theta$ (see Figure 10-2). Optically, this may seem inappropriate, as one is inclined to define the technological gap as the difference between some potential technological ceiling and the current level of technology. But such a ceiling can probably never be defined, and our measure, the magnitude $y - \theta$, measures the ease at which new technological improvements can be achieved. On more formal terms, the *smaller* the difference $y - \theta$ the higher the probability of finding technologies superior to the currect practice for a given rate of experimentation – a given n.

With our assumptions, Δy, the technological change, can be only positive – technology can only improve with time, closing the technological gap as it improves. Even if experimentation continues at the same rate (n = const.), technological change will decrease with time. Moreover, since the marginal expected returns to research will decrease with time (as the technological gap closes), optimal n will decrease with time, reducing even further the acceleration rate of technology. Eventually, a point will be reached at which expected returns will be smaller than the cost of a single observation, n = 1, research will stop, and technology will stagnate forever.

It is worthwhile to recall at this point the assumptions that led to our conclusions: (a) technology will stagnate so long as basic knowledge is constant (θ = const.); and (b) research will stop as its payoff diminishes. Even if θ = const., research will continue if technology deteriorates or is subject to obsolescence. This might be termed maintenance research – the research necessary to maintain current productivity levels.

The optimal rate of experimentation depends on the present value of future probable benefits from research $- 1/r[E(\Delta y)]$. The *lower* the rate of interest, the higher the present value of future benefits and the higher the optimal level of technological research. Like any investment, research (investment in knowledge) is a decreasing function of the rate of interest.

Scale can enter the economics of research in several ways. Evenson discusses the effect of the scale of the experiment station.[9] Here economies of scale in the creation of knowledge stem mainly from the interaction of scientists working in different disciplines and from the integration of research and graduate university training, factors which cannot be introduced into our model in its present, simplified one-product stage.

Another, different aspect of scale effect is the size of the industry which is affected by the new technology. The larger the industry, the higher the benefits to research. But, particularly in agriculture, size of industry as measured by acreage, for example, is also associated with diversity in conditions of production. In this case benefits will not be directly proportional to scale.[10]

Recall that the first stage in the development of the modern sugarcane va-

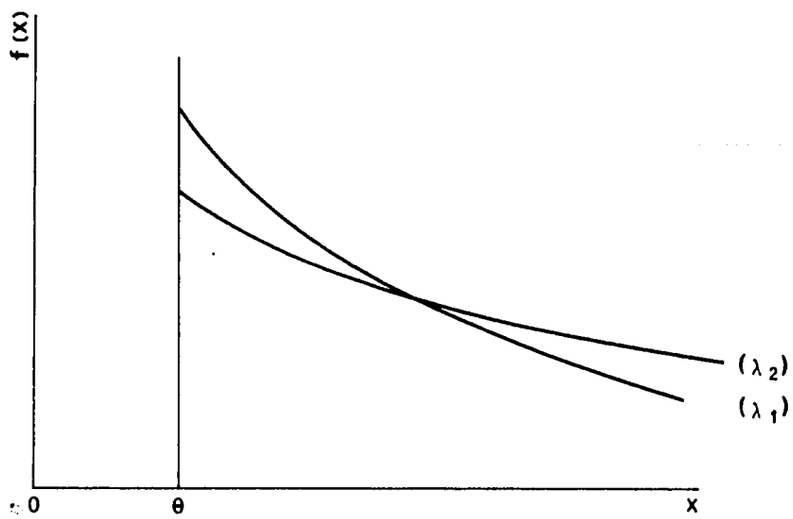

Figure 10-5. The effect of an increased variance $[\mathrm{Var}(x) = \frac{1}{\lambda^2}, \lambda_2 > \lambda_1]$.

rieties consisted, in fact, of the discovery of a variance-increasing technique. The importance of research designed to develop a genetic pool that incorporates greater diversity (variance) is not always properly appreciated. The collection of varieties, radioactive radiation, methods for creating new chemical compounds—all these are variance-increasing techniques which are followed by search and selection types of research work.

In our model the variance parameter is λ. (In the exponential distribution it is also the mean parameter $[E(x) = \theta + 1/\lambda]$.) Reducing λ will increase the probability of finding higher x values (see Figure 10-5) of improving technology. Often applied research will not be economically justified until ways to increase the variance of the samples observed are developed.

Basic Research

Basic research widens the technological gap and increases the probability of finding superior technologies. In our model, basic research will shift the parameter θ to the right (see Figure 10-6) and will increase optimal experimentation.

It is interesting to note here a *steady-state property*. Assume that basic research and applied research proceed at constant rates (per period $\Delta\theta$ = const., n = const.). Then the rate of advancement of technology in practice will ul-

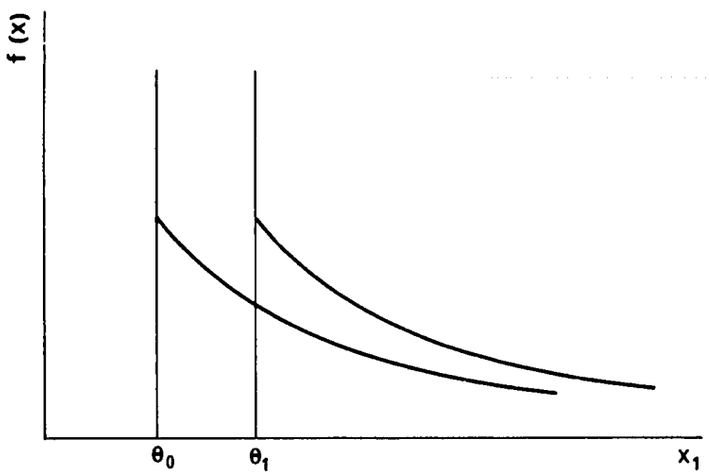

Figure 10-6. Basic research shifts the population searched to the right.

timately converge to the rate of advancement of basic knowledge. (A special case has already been encountered: in the absence of basic research, technology will eventually stagnate at a constant level.) The level of technological research in the steady state does not affect the *rate* of technological advancement, but only the *level* of technology in practice (see Figure 10-7).

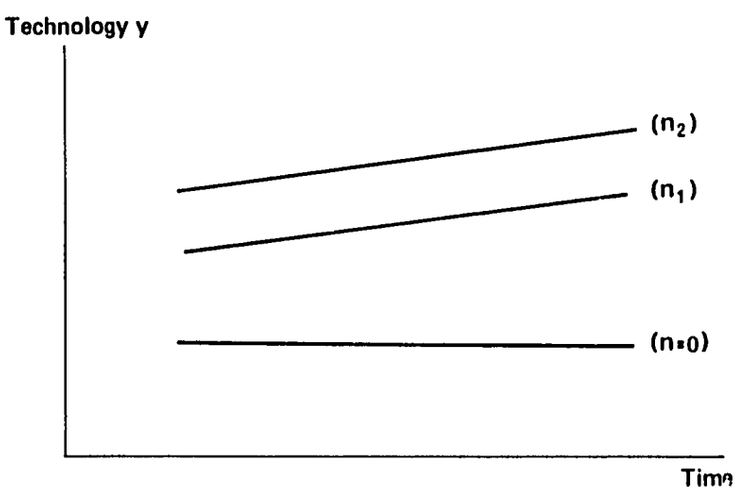

Figure 10-7. Time path of technology in the steady state at different levels of experimentation ($n_2 > n_1$).

The proof of the steady-state property is based on the fact that technological improvements at a rate faster than the advancement of basic knowledge will close the technological gap and decrease the probability of further technological change. Slower technological improvements will increase that probability. The endogenous variable in the system is the technological gap – it will be adjusted to maintain a steady-state equilibrium, with technological change fluctuating stochastically around a constant rate of change.

It can also be shown that in the long run, if basic knowledge proceeds at a constant rate, constant rate of experimentation is optimal. Thus in the long run the steady state is the optimal state of a research system fueled by a constant rate of new basic knowledge.

Concluding Remarks

Perhaps the most dramatic recent development in the field of agricultural research is the establishment of the international research centers. With their size and resources they can draw the best scientists, and they are well equipped to perform their task. Two elements contribute substantially to the success of these centers: (1) a wide technological gap – an example which comes immediately to mind is the case of the *Norin* 10 Japanese dwarf wheat variety which served as the basis for the development of the Mexican wheats and later provided principles for the breeding of the "miracle rice" varieties; (2) the large variance of the populations they search – the International Rice Research Institute (IRRI) alone has a collection of 30,000 rice varieties, and the International Center for the Improvement of Maize and Wheat (CIMMYT) performs tests all over the world. The subtropics and the tropics have been comparatively neglected in agricultural research, and the potential exists there for successful international efforts. (On these issues see chapters 7 and 9.)

Yet eventually, once the gap has been closed and the large variance exploited, the rate of progress of technology will be limited by the advancement of basic knowledge. Thus, in principle, the contribution of the international centers can be expected to decline in time (after an initial stage of acceleration).

The initial focus by the centers on wide-base technologies was clearly consistent with the objective of efficient use of research resources. Mexican wheats are now grown over large areas and under diversified geoclimate conditions. In following this procedure, the centers opened up technological gaps in the countries that were recipients of the new technologies and dramatically increased the payoffs to local adaptive research. Such explicit signals are being recognized by public authorities. As the potential gains are recognized, the effect is to expand and strengthen research institutions in many developing countries. The more successful the international centers, the more produc-

tive will local research work be. This will have a significant impact on the future role of the international centers. They cannot be expected to remain the sole producers of modern technology. Rather, additional emphasis will be given to their function as clearing houses for knowledge and genetic material. An excellent example is IRRI's recent International Rice Testing Program in which "scientists are cooperatively developing a 'critical mass' of genetic technology that will feed improved genetic materials and breeding information to scientists across the rice growing world." The main feature of the program is that "each nation contribute[s] . . . genetic materials, testing results and breeding information to help develop the critical mass effect."[11] Such developments will reduce the *relative* contribution of the international centers to global agricultural research. Furthermore, more effective scientific communication systems can be expected to reduce the importance of the geographic concentration of scientific work in one locality. These effects should not be expected to materialize fully in the near future, but the centers should be ready for them, as they should be welcome. The success of the international research efforts will induce competition among national systems. This result should be welcomed as an indication of the successful contribution of the institutes to global research capacity.

I have tried to point out clearly and explicitly the simplifying assumptions of the model presented in this chapter. I hope that despite its limitations the model can serve as a starting point for a theory of research and as a steppingstone for further analysis. Two reservations are worth mentioning in conclusion.

In the present formulation, basic scientific knowledge is exogenous to the applied research system. Ruttan has pointed out the reverse link whereby advances in technology – in instrumentation, for example – contributed to further advances in basic science.[12] Changes in factor supplies or in demand may also exert an independent impact on the productivity of technological research. This observation sheds strong light on the "system" nature of the science-technology complex which stretches even further. For example, the level and quality of university education is to a large extent a function of the quality of the research conducted at the institutes of higher learning. Thus a high-quality scientific community breeds the technical personnel that later conducts the applied and adaptive research. On the other hand, the demand for technical skills, if properly channeled, strengthens institutions of higher learning and "pure," basic science. (I am, of course, abstracting from a host of complicated and important issues which are outside the scope of our present discussion.) Against the background of this broad view, ours is a partial analysis – one building block of the system.

There remains one shortcoming in our understanding of the operation of

public research systems which I should like to reemphasize here, and this is the nature of the connection between the demand, or the payoffs to research, on the one hand, and the policy maker and the scientist on the other. What is the "market" in which such a system operates? What signals does it follow? What "profits," if any, are maximized? Hayami and Ruttan showed that research in Japan and the United States reacted efficiently to economic incentives.[13] Why did it not react in a similar manner in many other places? This gap in our knowledge and understanding is part of a larger gap: the lack of an economic theory of bureaucracy and our meager understanding of the process of economic development.

NOTES

1. This study was supported in part by the United States-Israel Binational Science Foundation.

2. Yujiro Hayami and Vernon W. Ruttan, *Agricultural Development: An International Perspective* (Baltimore and London: Johns Hopkins Press, 1971).

3. An exception is the "innovation possibility frontier" suggested by Charles Kennedy, "Induced Bias in Innovation and the Theory of Distribution," *Economic Journal*, 74 (1961), 541-547. For a critique of Kennedy's model see H. P. Binswanger, "A Microeconomic Approach to Induced Innovation," *Economic Journal*, 84 (1974), 940-958. See Hayami and Ruttan, *Agricultural Development*, for references to other sources on these issues.

4. G. J. Stigler, "The Economics of Information," *Journal of Political Economy*, 69 (1961), 213-215. R. R. Nelson, "Uncertainty, Learning and the Economics of Parallel Research and Development Efforts," *Review of Economics and Statistics*, 43 (1961), 351-364.

5. This is a nonmathematical exposition. For rigorous formulations and proofs, see Robert Evenson and Yoav Kislev, *Agricultural Research and Productivity* (New Haven: Yale University Press, 1975), chapter 8.

6. B. Epstein, "Elements of the Theory of Extreme Values," *Technometrics*, 2 (1960), 27-41.

7. R. R. Nelson and Edmund S. Phelps, "Investment in Humans, Technological Diffusion, and Economic Growth," *American Economic Review*, 56 (1966), 69-75.

8. Robert E. Evenson and Yoav Kislev, "Research and Productivity in Wheat and Maize," *Journal of Political Economy*, 81 (September-October 1973), 1309-1329.

9. Robert E. Evenson, "Economic Aspects of the Organization of Agricultural Research," *Resource Allocation in Agricultural Research*, ed. Walter L. Fishel (Minneapolis: University of Minnesota Press, 1971).

10. For an empirical attempt to cope with some of these problems see Evenson and Kislev, "Research and Productivity in Wheat and Maize."

11. *IRRI Reporter* (Los Baños: International Rice Research Institute, February 1975).

12. Vernon W. Ruttan, 1975, personal communication.

13. Hayami and Ruttan, *Agricultural Development*.