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TECHNOLOGICAL POTENTIAL FOR INCREASING CROP PRODUCTIVITY IN DEVELOPING COUNTRIES

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The potential for increasing food production can conveniently be considered for the short, medium, and long run. In the short run, increased food production can only come from fuller use of existing technologies. Wide spread use of known technologies occurs in response to changing incentives that make them more attractive, by increasing farmers' knowledge of the technologies and by assuring adequate supplies of inputs to be used as part of the technologies to increase production. All these changes require political and economic policy changes that may be forthcoming with a demonstration of great unexploited technical potential for increased production.

In the medium run, adaptive research to change production technology and investments to change the environment to make existing technologies more attractive is the principal source for increasing production. Adaptive research may include technology transfer, although the potential for direct transfer across agricultural ecologies is limited.

In the long run, advances in basic science and its applications to agricultural production many be the major factor determining rates of output increase. The theoretical possibilities offered by recombinant DNA and other biotechnology techniques appear to be very large, but until there has been more experience with such technologies there is little one can say about their potential in the developing world. Of course, if these technologies are not applied to agricultural production problems of developing countries, production cannot improve and retrogression may occur in these countries. These possibilities have prompted the Rockefeller Foundation to support a program of biotechnology research on rice, a crop of immense importance for the developing world. That program is a vehicle for training researchers from the developing world in the techniques of biotechnology. This paper will, however, concentrate on the short- and medium-run potential and not discuss the possibilities or potential problems raised by biotechnology.

Will Proven High Productivity Technology Spread Further?

Existing high productivity technology can contribute to further increased production if its use is extended to new areas. What is the potential for further spread of semidwarf wheat and rice technology?

Dalrymple has monitored the spread of semidwarf varieties in a series of publications that show rates of adoption of semidwarf wheat and rice for principal producing countries in the developing world (7,8,9).[2] By 1982-83, semidwarf varieties had spread to about 50 percent of the wheat and rice areas, leaving an apparent ample scope for further spread. However, examination of their spread across countries shows that their rate of spread has slowed (figs. 1-2). Analysis of semidwarf rice varieties in India shows that in major producing states (such as Andhra Pradesh and Tamill Nadu) adoption reached its plateau by the midseventies. In the eastern states (Orissa, Bihar, and West Bengal) adoption was slow but picked up in the midseventies, and in other states adoption had slowed by the late seventies (fig. 3). Adoption, measured as a proportion of rice area, is high in some states (Punjab and Haryana) and very low in others, especially in eastern India. Concentration was initially associated with

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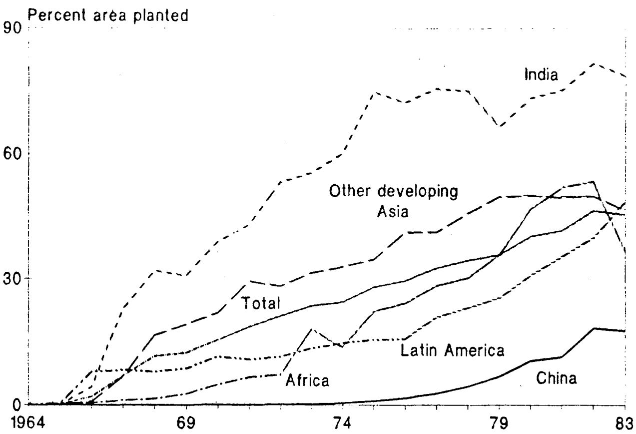
[2]Underscored numbers in parentheses are listed in the References at the end of the article.

Figure 1

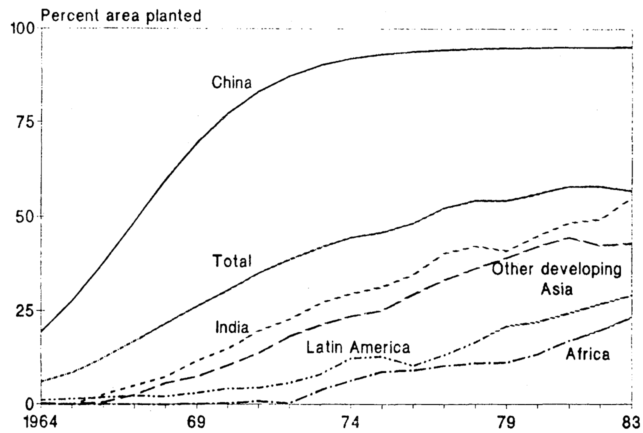
Adoption of semidwarf wheat varieties in major developing countries and regions



1/ Source: (7, 8).

Figure 2

Adoption of semidwarf rice varieties in major developing countries and regions



1/ Source: (7, 8).

irrigation, and, when most of the irrigated area was planted to the semidwarfs, the rate of spread slowed considerably (20,33). Walker and Singh argued that high-yielding varieties of sorghum and millet have reached a plateau of adoption in India (45). Thus, while there is still some scope for further spread of semidwarf varieties, it is unlikely to be rapid, and, because they will spread onto nonirrigated or newly irrigated land, the associated productivity gains on the new areas will be considerably lower than on the initial adoption areas.

Intensification

What scope exists for further intensification of production practices where semidwarf varieties are now grown? This could be answered with good production function estimates that separate the effects of fertilizer, irrigation, and variety. Because varieties, fertilizers, and irrigation are complementary, they are used together by farmers and so multicollinearity makes estimating the production function from farm surveys extremely difficult and yields unreliable results. For that reason, I developed an analysis that uses a land-quality based approach to analyze the contribution of each input in the case of semidwarf rice (20).

This model has been used to ask what is likely to happen with increases in fertilizer availability, with more rapid spread of irrigation, with changes in the supply of fertilizer or rice prices, and similar questions. A complete discussion of the model and results of its application is beyond the scope of this paper, but a few highlights are useful.[3]

The model distinguishes five different production technologies by irrigation and variety type. The use of fertilizer is closely associated with the use of modern rice varieties, which, in turn, are closely associated with the availability of irrigation. Some rainfed areas are planted

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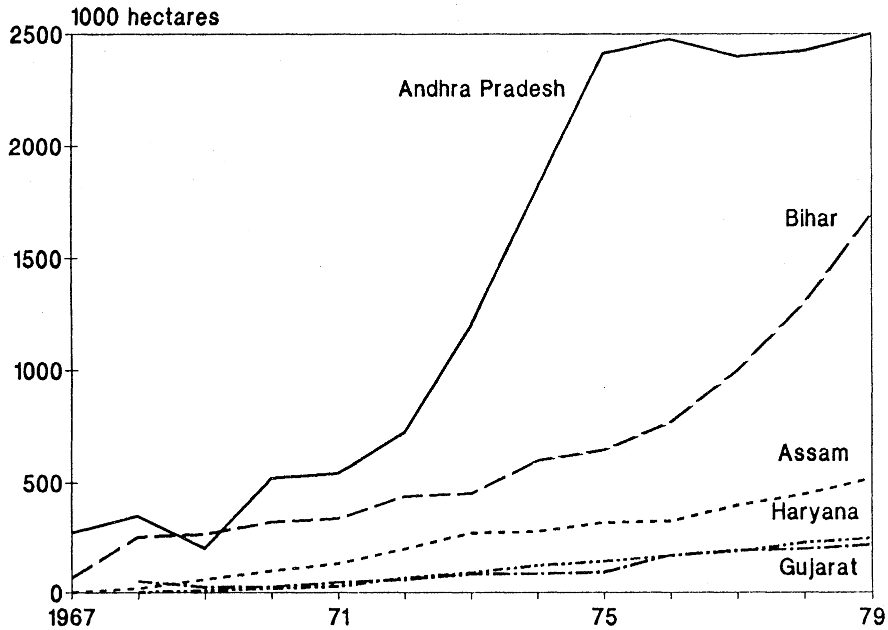
[3]Further details are available in Barker and Herdt (2, p. 18).

Figure 3

Adoption of semidwarf (HYV) rice varieties in states of India



to semidwarfs, but they are mainly grown with irrigation and are expected to spread slowly to rainfed areas. The model shows that if, between 1980 and 2000, irrigated areas grow at the historical rate new planted, modern rice varieties will continue to spread at a rate similar to the historical pattern and ferilizer availability will grow at 5 percent per year. The use of modern technology will reach the levels indicated in table 1, with an output of 409 million tons. Individual models were developed for eight countries that produce 85 percent of Asia's rice.

The adequacy of this level of production can be judged only by comparing it with the projected level of demand. Demand was projected using income and population growth rates and income elasticities shown in table 2. Most projection exercises assumed that any shortfall between future demand and production will be covered by imported rice, but our model incorporates the price elasticities of demand, thereby permitting a determination of the price implications of alternative import policies.

Table 1 shows that with the base run supply projection only Thailand will export in the year 2000, when net imports for the eight countries are projected to reach 35.4 million tons in order to hold real prices constant. If self-sufficiency (zero imports) is imposed, rice prices are projected to be nearly double their 1980 levels by 2000 and per capita consumption is projected to fall from its 1980 level of 135 kilograms (kg) per capita to 126 kg per capita.

Under these projections, most countries will reach, with present technology, rather high levels of fertilizer application, and modern varieties will have spread about as widely as one could expect, given each country's irrigation capacity.

The data appears to indicate considerable scope for the extension of irrigation, especially in Thailand, Burma, and Bangladesh, as well as in a number of other countries where only half to two-thirds of the rice area is projected to be irrigated in the year 2000. However, irrigation is expensive, and its construction is also constrained by the capacity to mobilize the necessary human and physical capital resources in most countries. It is my view that it is highly unlikely that irrigated area can grow significantly faster than is reflected in table 1, but to

Table 1--Base run projections of rice production, consumption and prices for selected Asian countries for the year 2000.

Country	Production 1/	Fertilizer	Area: MVA	Area: Irrigation	With zero imports: Price	With zero imports: Consumption	With imports to hold price at 1980 level: Consumption	With imports to hold price at 1980 level: Imports 2/
	Mil. mt	Kg/ha	Percent	Percent	1980=100	Kg/capita	Kg/capita	Mil. mt
China	196.1	148	3/ 65	94	113	109	116	6.0
India	99.4	67	68	51	210	69	89	13.0
Indonesia	34.1	89	74	84	380	112	204	8.5
Bangladesh	28.7	32	63	24	171	144	188	5.4
Thailand	23.8	25	18	41	4/ 100	4/ 201	201	-.3
Burma	14.7	71	5/ 56	21	127	178	195	.6
Philippines	9.6	61	89	42	225	82	114	1.7
Sri Lanka	3.1	102	73	66	207	99	141	.5
Total or average	408.8	75	64	54	192	126	156	35.4

1/ Rought rice.
2/ Milled rice; negative sign indicates exports.
3/ Hybrid rice.
4/ Exporting nation, assumed to continue exports.
5/ Includes modern and "improved" varieties; the balance are traditional varieties.

Source: (20)

Table 2--Annual growth rates of population and income, and elasticities of demand with respect to income and prices used in the rice projections model.

Country	Projected growth rate of--: Population 1/	Projected growth rate of--: Income per capita	Elasticity: Income	Elasticity: Price
China	1.2	2.0	0.45	-0.50
India	1.8	2.0	.45	-.50
Indonesia	1.5	5.0	1/ .50	-.60
Bangladesh	2.5	2.0	.45	-.50
Thailand	2.3	5.0	.05	-.30
Burma	2.4	2.0	.30	-.40
Philippines	2.7	3.5	.25	-.40
Sri Lanka	2.3	2.0	.40	-.60

1/ Value for 1980-85. Because of the rapid growth of per capita income, the income elasticity was assumed to decline by 0.1 ever subsequent 5-year period.

Source: (20).

determine the potential effect of greater investments in irrigation, a rapid growth scenario was developed in which it was assumed that irrigated rice area grew at twice the rate of the historical period.

That scenario shows significant difference in the percentage of area irrigated in the year 2000 in countries where irrigation increased rapidly since 1960, but where irrigation either spread slowly or where a very large proportion of the rice area was irrigated in 1980 there was little difference. Average irrigated area for the eight countries would reach 62 percent compared with 54 percent in the base run situation, and modern varieties would reach 72 percent of the total rice area. Under this scenario, rice production is projected to reach 466 million tons, net imports would reach only 13.6 million tons, and, Thailand, Burma and Sri Lanka would export rice if prices are held at 1980 level. If imports are constrained to zero, rice prices would increase by only 30 percent, and per capita consumption of rice would increase to 144 kg.

Obviously, output growth dependent on irrigation investment comes at a cost to the economies involved. Food imports are also costly and require recurring annual foreign exchange costs. The fast rate of output growth requires substantially higher irrigation investments than the base run, but because of the extra output produced, food import costs are lower in subsequent years. This effect is illustrated in table 3. It was estimated that in 1985 annual expenditures of $5 billion would be required to hold real rice prices constant following the base run scenario. The fast output growth scenario, which produces net exports in 1985, has a lower net cost, although its irrigation investment cost is almost twice that of the base run. By the year 2000, annual expenditures of $16 billion are required even in the fast output scenario, with about one third required for imports. The base run scenario requires annual expenditures of $20 billion, with most of that going for rice imports.

It appears that increases in the productivity of fertilizer and irrigation are necessary if developing countries are to meet their needs for rice through the year 2000. An indicative projection assuming such increases in productivity was made to determine how great a productivity gain would be adequate. To illustrate the type of assumption, the production function for irrigation semidwarf varieties in the base model for the Philippines reaches a maximum of 2.9 tons per hectare (ha) at 105 kg of fertilizer nutrients in the basic model. In the enhanced productivity indicative projection, it reached a maximum of 4.4 tons per ha at 128 kg of fertilizer nutrients in the year 2000. This productivity is within the potential of genetic material now available but is not being reached on average across all rice farms in the Philippines. To raise the average productivity to that level, I believe it will be necessary to either produce better varieties or teach farmers how to better exploit the existing ones--both require continued investment. An increase in productivity would enable the Philippines to keep up with demand through 2000; comparable increases in productivity would enable other countries to do likewise.

This analysis convinces me that there is little significant "unused potential" in current rice technology and that continued improvements in technology as well as increased fertilizer use and irrigation investments will be needed to produce enough rice to adequately feed Asians over the coming several decades. Similar studies, to my knowledge, are not available for wheat, but current data indicates rapidly increasing wheat imports in the developing countries (4). However, it is difficult to determine the potential for further intensification of wheat production without a detailed anaylsis. An alternative is to examine the demonstrated level of potential yields.

Table 3--Annual expenditures associated with two alternative scenarios of the future rice situation in eight Aisan countries 1/

Year	Base run scenario				Fast output scenario			
	Irrigation	Fertilizer	Net imports	Total	Irrigation	Fertilizer	Net imports	Total
				Million US$				
1985	1,741	1,410	1,903	5,054	3,224	1,500	-270	4,454
1990	1,815	1,720	6,195	9,730	3,458	1,906	1,755	7,119
1995	1,917	2,030	10,955	14,902	5,954	2,272	4,515	12,741
2000	2,051	2,407	15,972	20,430	7,199	2,818	6,000	16,017

1/ Irrigation costs are annual investment costs; fertilizer costs are the value of fertilizer used in rice production at a price of US$225 per metric ton of area; import costs are calculated by assuming a price of US$300 per metric ton of milled rice.

Raising Farmers' Yields to Their Maximum Potential

Some analysts have approached the issue of potential food production by determining the biomass production capacity of green plants and by determining food production by adjusting for nonconsumable portions (46). This approach may be suitable for determining some ultimate food production potential, but it is not appropriate for a 20-to-40 year projection period. There also is literature reporting production functions based on farm survey data, but because they are based on farmers' practices, they cannot be used to reflect potentials that exceed those levels. Only experimental data can provide an acceptable reflection of potential productivity that is demonstrated but not yet applied.

Factors that Contribute to Crop Yield

Crop variety, fertilizer nutrient level, pest control, and water availability are all important factors. Planting date, soil chemical characteristics, drainage, and weather conditions at harvest are less often mentioned but are also important. Economists seldom recognize the effects of solar radiation and temperature, but to crop physiologists, they are the overriding factors determining potential yields. Thus, depending on what factors are controlled at what levels, one may define or observe a number of differnt yield levels that may be thought of as "the maximum potential." Therefore, some definitions are necessary.

For convenience in defining these concepts, the terms "experiment stations," "onfarm trials" and "farmers' fields" are used. Each is understood to be representative of such conditions in the region of interest. "Environmental conditions" and "management factors" are used to mean roughly noncontrollable and controllable factors. Roughly is used because given enough money one can control all the factors necessary to grow bananas at the earth's poles! Experiment stations are observed to have invested more than most farmers in controlling environmental factors, and while there is a continuum between farmers' fields and experiment stations, there is an observable difference between the typical farm and the typical experiment station, which is important for this discussion.

Researchers must choose levels for all controllable factors when running yield experiments. When the objective is to obtain maximum yields, it is natural to try and set all factors at nonconstraining levels. But such experiments may not reflect "realistic" potentials for farmers. Table 4 presents a classification of the various measures of potential yields. Sunlight and the innate capacity of the plant are constraining in all such experiments. "Noncontrollable" environmental factors may be modified in a laboratory but not in experimental fields. Test factors are varied within an experiment, nontest factors are held constant, but both are controllable. Other related factors are all other things, usually environmental, that can only be controlled at a cost. The highest yields are generally measured when fewest factors are constraining; hence, it is important to recognize which definition of potential yield is being used.

The physiological potential is defined here as the maximum photosynthetic capacity of a plant to produce dry matter, unconstrained by pests, nutrients, water, or any other production constraint. "Swaminathan stated "It is, in a way, the most optimistic estimate of crop yield based on present knowledge and available biological materials under ideal management in an optimum physical environment" (41). The physiological potential is basically dependent on the level of solar radiation and the innate photosynthetic efficiency of the particular plant (48). Because it is impossible to control all factors in field production, this is essentially a theoretical yield, not observable except perhaps under the most restrictive greenhouse conditions.

The experiment station maximum yield is a somewhat less restrictive concept and is defined so as to be observable. It is the yield produced under experiment station conditions where "all" controllable factors are held at their maximum yield level. Even this concept entails some

Table 4--Factors that constrain yields in major types of agri. experiments used to measure potential yields

Contraining factor	Definition of potential yields						
	Maximum physiologic potential	Experiment station			Onfarm trials		
		Maximum	Optimum input	Theoretical optimum	Maximum	Theoretical optimum	Optimum input
Sunlight, plant capacity	CF	CF	CF	CF	CF	CF	CF
Noncontrollable environment	CF	CF	CF	CF	CF	CF	CF
Test factors (controllable)			EV	EV	EV	EV	EV
Nontest factors (controllable)				TO		TO	CF
Other related factors					CF	CF	CF
Are yields observable or theoretical?	T	O	O	T	O	T	O

CF = Contraining, that is researcher cannot or has not changed to nonconstraining level.
Blank = Factor has been modified by researcher to a nonconstraining level.
EV = Factor is varied in the experiment.
TO = Assumed to be at its theoretical economic optimum.
O = Observable
T = Theoretical.

difficulties. Yields vary from replication to replication, season to season, and year to year simply because of the variability in soils and crop production conditions. A good quantitative estimate of the experiment station potential yield, therefore, should be obtained as an average of a number of maximum yield experiments.

It is possible to compute <u>experiment station optimum input</u> yields for two or three principle manageable inputs. These are the yields obtained when inputs are applied to their economically optimal levels. Sometimes a comprehensive production function can be estimated, but more often a series of single-input response functions must be used because of limitations in the experimental designs used. These computed optimal yields will, in general, differ from onfarm optimum input yields because of the practice of holding nontest and other related factors at a high level in experiment station research.

The experiment station theoretical optimum yield is the yield that would be obtained if all inputs were set at their economically optimal level, given the other related factors prevailing on the experiment station and the prevailing prices of inputs and products.

This is a theoretical concept. It is generally impossible to calculate the optimal level of each input because even using very large experimental data sets and advanced computational techniques it is difficult to obtain quantitative estimates of diminishing marginal productivity for each manageable input.

<u>Onfarm trials maximum</u> yields can be observed from experiments in farmers' fields in which controllable inputs are held at their maximum yield levels by researchers or from maximum yield contests or demonstrations designed for the purpose. These yields will generally be lower than maximum experiment station yields because other related factors cannot be controlled in farmers' fields. Data are generally reported as averages for a number of separate trails because of the variability between sites.

<u>Onfarm trials theoretical optimum</u> yields can be defined in a similar way as the experiment station theoretical optimums, but from farmers fields experiments. As with experiment station theoretical optima, these are impossible to either observe or compute because it is practically impossible to obtain estimates of multiple input production functions in which all inputs show diminishing marginal returns (<u>21</u>,<u>37</u>).

Onfarm trials optimum input yields are defined as the yields obtained when the test factors are set at their economically optimal level, but nontest factors and other related factors are at farmers' levels. Such onfarm optimum input yields cannot be directly observed but may be computed from appropriate estimates of the response functions for several test inputs.

Farmers' yields in onfarm trials are the reseachers' attempt to simulate farmers' actual practices under their environmental conditions but within an experiment so input levels and yields can be accurately measured. This will provide an accurate indication of yields on the sample of farms where the experiments are conducted, but may not be representative of a wider population of farmers.

Average yields are the level reported in official statistics for a country, province, or region for which such statistics are estimated. They may differ from the farmers' yields in onfarm trials because of differences in measurement techniques (crop-cut versus estimate) and differences in geographic coverage.

An economically recoverable yield gap is the difference between average yields and farmers' fields theoretical optimum yields for a given place. It cannot be observed except in very special circumstances because farmers' optimal yields cannot generally be observed. Instead, various approximations are used, depending on the availability of data.

It is clear that for an economically recoverable yield gap to exist, the difference between farmers' yields in onfarm trials and maximum yields in onfarm trials must be relatively large to allow for the difference between maximum yield input levels and economically optimal input levels. The difference increases as environmental constraints, complexity of cropping systems, costs for credit, risk allowances, and marketing costs increase.

Yield Gaps in U.S. Agriculture

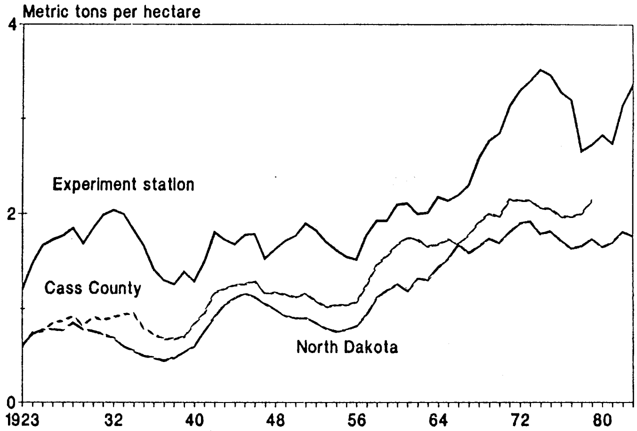
It is normal to observe a substantial difference in yield between experiment station and average yields. Data from the United States illustrate the point. Figures 4-5 shows North Dakota experiment station, and Cass County average wheat yields during 1923-83 (14). For the 1923-32 decade, experiment station's yields were 112 percent higher than the county's average yields; for 1943-52, they were 49 percent higher; and during 1967-76, they were 55 percent higher. The experiment station yields during 1923-83 were on average 64 percent higher than the county yields and 98 percent higher than North Dakota yields. Average farm yields increased 112 percent from the 1923-28 period to the 1973-78 period, while experiment station yields increased 66 percent. In the early sixties, corn yields averaged 1.5 tons per ha, while experiment station yields were nearly 4 tons per ha. By the early eighties, State yields had increased to 4 tons per ha, while station yields were 7 to 8 tons per ha.

A comparison for soybeans shows a similar phenomena (fig. 6). These data match results from 63 experiment stations with the average yields in the counties in which they were located (38). In 1943-47, the experiment station yields were 73 percent higher than the county averages. For 1959-63, they were 69 percent higher, and for 1975-79, they were almost the same percentage higher. Average yields increased about 40 percent over the period, and average experiment station yields increased 35 percent.

In Illinois, the Morrow plots have demonstrated, for more than 100 years, the effect of different soil management treatments on corn and other crop yields. While not strictly a maximum yield experiment, various treatments have been designed to demonstrate high yields and provide a basis for our comparison (43). The Allerton Trust Farms in Piatt County were deeded to the University of Illinois in 1946. They are not experimental but "are managed to produce maximum income to support the operation and maintenance of the Robert H. Allerton Park and Conference Center" (42).

Figure 4

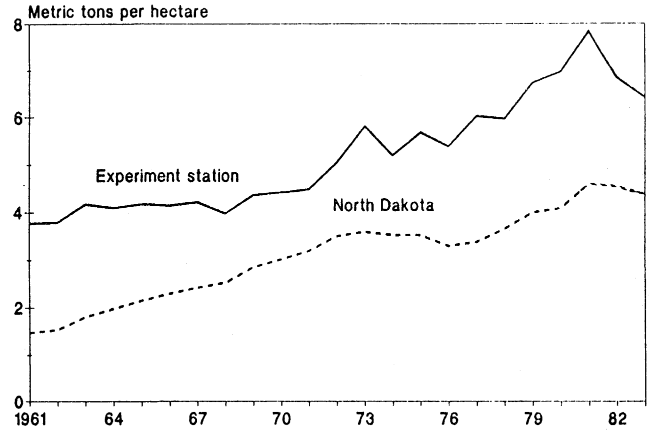
Average farm yields, 5-year averages, North Dakota wheat



Sources: (14, 30, 44).

Figure 5

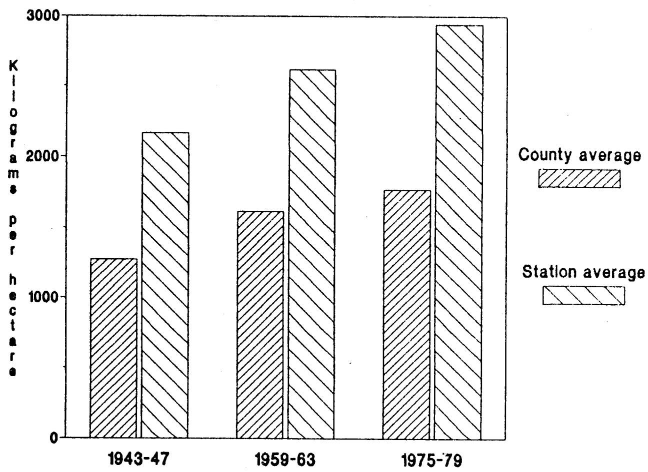
Average farm yields, 5-year averages, North Dakota corn



Sources: (14, 30, 44).

Figure 6

Average county and experiment station yields of soybeans from 63 locations, United States



Source: (38).

A comparison of Morrow, Allerton, Piatt County, and State average yields is shown in table 5. Morrow plot yields remained substantially above Allerton farm and county averages over the entire period, even though there was some variation (table 5). In the seventies, county average yields approached Allerton farm yields, but experiment station yields maintained an advantage over both. Allerton corn yields increased 54 percent from 1950-55 to 127 bushels per acre (8.0 tons per ha) in 1972-76, soybean yields increased by 22 percent to 37.8 bushels per acre (2.5 tons per ha); county average yields for the two crops increased by about the same proportion.

Table 5--Experiment station, university farm, county, and State average corn and soybean yields, Illinois

Commodity and year	Experiment station (Morrow plots)1/	Allerton Trust Farm	Piatt County	State average
		Metric tons per ha		
Corn yields:				
1955-59	6.7	5.4	4.8	4.1
1965-69	9.4	6.3	5.3	5.8
1972-76	9.4	8.0	8.0	6.4
Soybean yields:				
1966-70	3.8	2.7	2.4	2.1
1972-76	2.9	2.5	2.4	2.1

1/ Yields from plot 4, MLP + LNPK treatment, a rotation of corn-oats from 1955 to 1966 and corn-soybeans from 1967 to the present. Each point is the average of 3 years of observations rather than 5 because corn was alternated with the other crop on this plot.

Sources: (42, 43).

The long continuation of a yield gap in several U. S. situations illustrates that this is a normal situation and cannot be taken as a priori evidence of exploitable technology. The dramatic difference in the gap between experimental and county average yields, on the one hand, and maximum profit and county average yields, on the other, also suggests that one should look carefully at experiment station yields before implying that they reflect yields that could be economical.

Potential Yields of Principal Developing Country Crops

Semidwarf rice and wheat varieties were the basis for the "green revolution" that many observers reported about in the late sixties and seventies. Maize, sorghum, and millets have not seen nearly as many widespread technical changes in the developing countries.

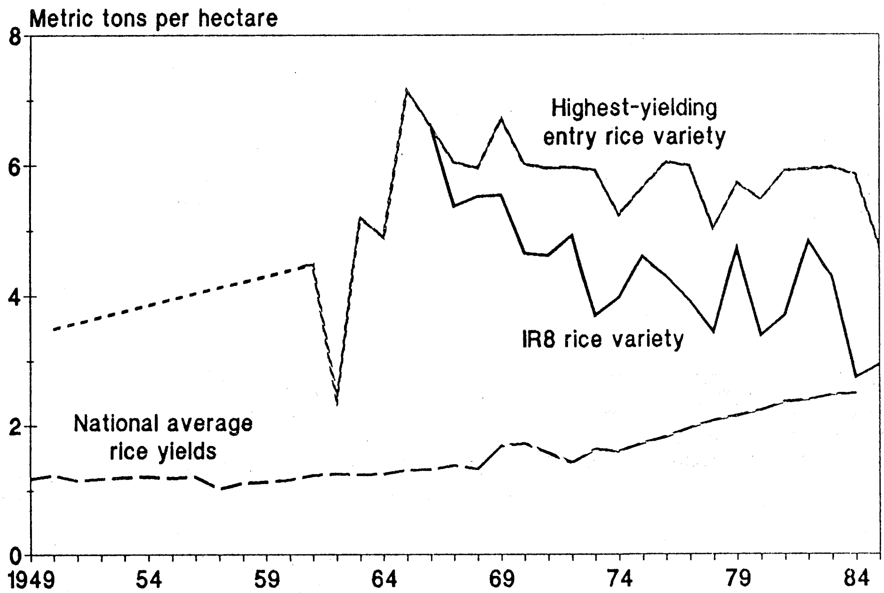
Rice

The first semidrawf rice varieties (IR8 and TN1) released to developing country farmers in 1965 had their shortcomings, but they were extremely high yielding as long as insects and diseases were absent. When such pests attacked them, they quickly succumbed. A series of newer, much more insect and disease resistant varieties have been produced by International Rice Research Institute (IRRI) and the rice research programs of the Asian countries since 1965. One of these, IR36, was estimated to have been planted to 20 million ha during the early eighties, but newer varieties had largely, but not completely, displaced it by 1985. Even IR8 is still planted by farmers in some areas where disease and insect pressure is minimal.

Casual familiarity with these facts has led many observers to assume that the rice varieties developed in the 20 years since IR8 was released must be higher yielding than IR8. However, examination of the available data do not support that and, in fact, tend to suggest the opposite. Figure 7 shows experiment station yields of the rice varieties available in the Philippines prior to the release of IR8 and, being in 1966, average experimental yields from a

Figure 7

Potential yields on newly released rice varieties in the year of release, Philippines



Sources: (5, 15, 32).

long-term set of fertilizer response trials organized by IRRI and conducted on three widely dispersed Philippine government research stations and at IRRI (15, 23).

There was a sharp increase in the yield of the highest-yielding entry from around 5 tons per ha in 1960 to over 7 tons per ha in 1965 when IR8 was released. Thereafter, yields are shown for the approximate "experiment station optimum input" yield level of IR8 and the highest-yielding variety tested.[4] Yields of IR8 declined after 1965, and yields of the highest-yielding entry also declined, although less rapidly. They certainly did not show an increase over time.[5] This is not to suggest that the newer rice varieties do not have advantages over IR8. Their yields are much more stable in the presence of insects and diseases than IR8, and they mature in fewer days, thereby permitting intensification of land use. However, they do not have any higher yield potential than IR8.

Comparing the national average rice yields in the Philippines with the average experiment station yields makes clear how farmers have been "catching up" with the potential created by the innovation of the sixties. The same picture would emerge from a comparison of rice yields in other countries with the potential.

Experimental evidence comparing rice farmers' production practices with onfarm trials maximum yields also suggests rather modest differences. In over 450 experiments, carried out in 9 provinces of 6 Asian countries over a period of 3 years, the difference between farmers' average yields and average yield with the high-input package was 33 percent or about 0.9 tons per ha in the wet season. Of that difference, failure of farmers to apply the optimum level of fertilizer accounted for 22 percent, or about 200 kg per ha in a group of farms where

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[4]Yields are averages across four stations and for wet and dry seasons at maximum yield fertilizer level for each season.

[5]An analysis of the 1966-80 data from this experiment is presented in Flynn and De Datta (15).

yields averaged about 2,700 kg per ha (19). This is quite different from the average yield gap of 900 kg per ha that was observed in the experiments, and even more dramatically different from the yield gap between the experimental yield of 6.8 tons per ha and the national level of 2.5 tons per ha in the Philippines (22).

My conclusion from this large body of data and analysis stands: "what is technically possible is more modest than what most observers admit; the economics of substantially higher yields are not attractive; the costs associated with the credit and tenure arrangements that often prevail in developing countries make higher input use totally unattractive to some farmers. Thus, the available technology is being used to its potential. If further growth is to be realized, continued development of technology must be combined with institutional reforms that make current technology attractive to users" (19).

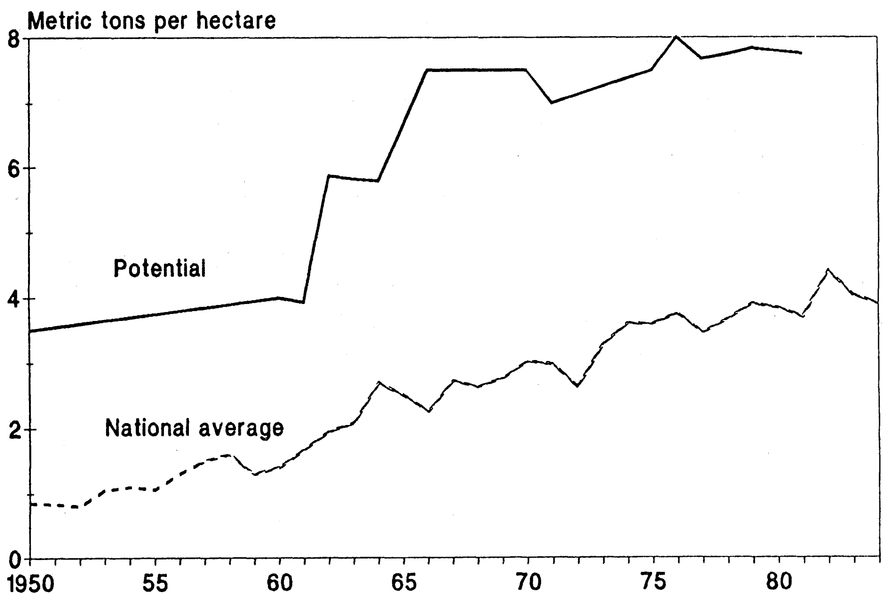
Wheat

Reported "potential" yields for semidwarf improved wheat varieties developed by CIMMYT and the Mexican agricultural research establishment and released in Mexico since the early fifties are shown in figure 8. Unlike the rice data, there is an indication that wheat yield potential has continued to increase since 1965. The increase has been rather slow, and, in recent years, modest compared with the breakthrough between 1961 and 1966. As with rice, the difference between national average yields and the potential as measured in wheat the experimental data has been eroding since the midsixties.

Some onfarm research evaluating the economically recoverable yield gap for wheat in India is summarized in table 6. There the "economic yield potential" has been calculated by taking into account the total cropping pattern (in which wheat often must be planted "late" because of other crops), the available irrigation water, and the profitable level of inputs as estimated in onfarm experiments (3). The results show that the economically recoverable yield gap is in the 0.8-1.3 tons-per-ha range, not the 3-4 tons per ha implied by a comparison of experimental and average farm yields. Still, as Byerlee and his colleagues point out, a yield gap of 1 tons per ha is worth making an effort to understand and recover.

Figure 8

Potential yields on newly released wheat varieties in the year of release, Mexico



Sources: (5, 15, 32).

Table 6--Estimated yield gap for wheat considering total productivity of cropping pattern and irrigation water availability, India

Item	Cropping region and system		
	Punjab Rice/wheat	Punjab Cotton/wheat	NWFP 1/ Maize/wheat
		Tons per hectare	
Farmers' average yield	1.8	2.2	2.8
Economic yield potential 2/	3.0	3.0-3.5	4.0
Yield gap:	1.2	.8 - 1.3	1.2
Volume		Percent	
Share	40	27-37	30

1/North West Frontier Provinces.

2/Based on results of onfarm experiments.

Source: (3).

Maize

The maize story is more complex. There was no dramatic spread of semidwarf or other "new" maize varieties in the developing world, as with wheat and rice, even though many institutions have been involved in maize and wheat research. Reasons for this difference are complex and beyond the scope of this discussion, but because the research system has been active, there is a large body of data that can be examined to determine the performance of the available technology.

Among countries in Africa, Kenya has had a rather active and successful maize research program. Figure 9 shows the potential yield of maize varieties released by the Kenyan national program for the "high ecozones" along with averages national yields (32). It is evident that considerable progress has been made since 1960 in improving the potential yields of maize varieties suitable for ecozone. Only a few varieties has been released for the "marginal" ecozones, and those have much lower potential yields. National yields, at least as reflected in Food and Agriculture Organization (FAO) data, have not increased in any perceptible way, raising the question of why. Similar lack of maize yield improvement is evident in other African countries. Many national breeding program have been producing improved maize varieties, some using maize germplasm from CIMMYT in their own breeding and others simply selecting varieties from material supplied by CIMMYT. Recent reports on the performance of CIMMYT maize germplasm consolidate results from experimental variety trials at a large number of sites in Latin America, Africa, Asia, and the Middle East.

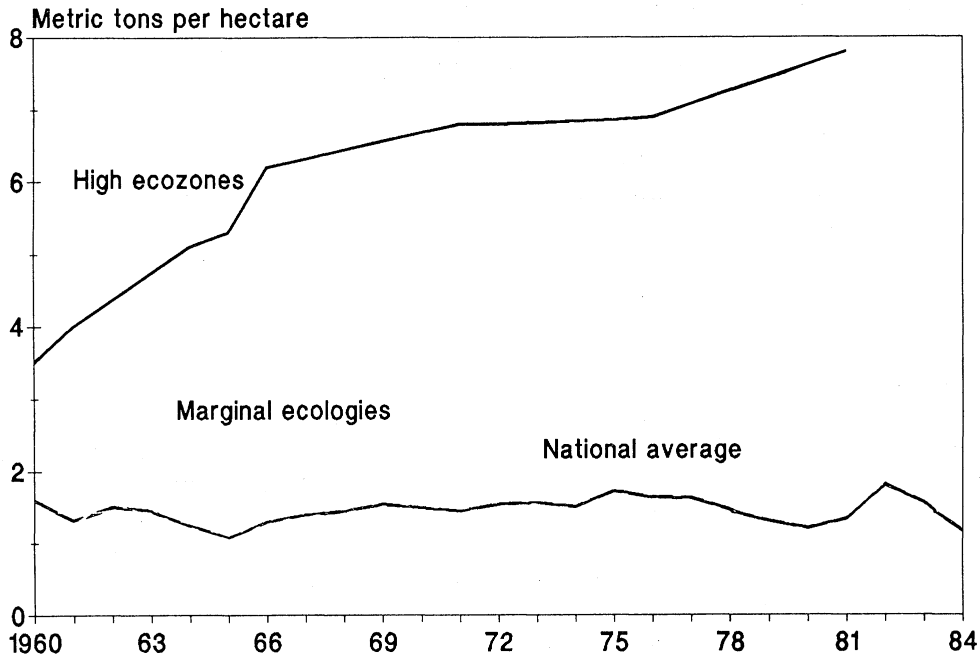
In trials conducted during 1982-84 at 94 experiment station sites in the developing countries, intermediate maturity, white CIMMYT maize yielded an average of 4.0 tons per ha. In trials at 151 sites between 1979-84, late maturity, white CIMMYT maize yielded an average of 5.0 tons per ha (34). These experimental yields are far above the average 2.0 tons per ha yield of maize in the developing world over the same period (13).

A recent paper compared the performance of CIMMYT maize with local checks in 12 countries of eastern and southern Africa, 11 countries in west Africa, and 3 countries in central Africa in experiment station trials between the midseventies and 1982 (16). The local checks were improved varieties, sometimes the widely grown hybrid SR52.

In eastern and southern Africa, the CIMMYT maize averaged 5.8 tons per ha compared with 5.2 tons per ha for the checks; in central Africa, it was 7.2 tons per ha compared with 6.2

Figure 9

Potential yields on newly released maize varieties in the year of release, Kenya



Sources: (5, 15, 32).

tons per ha for the checks; and in west Africa, it was 5.0 tons per ha compared with 4.3 tons per ha for the checks. Average maize yield for 1976-80 was 1.3 tons per ha in eastern and southern Africa, 0.7 tons per ha in central Africa, and 0.8 tons per ha in west Africa (13). Not only did the CIMMYT varieties far exceed national averages, but the local checks also exceeded national averages. There was little difference between CIMMYT maize yield potential and varieties already "available."

These data suggest there is a large yield gap between the technology presently being used by farmers and that which is available. To see how improved maize technology performs under farmers' conditions in order that this gap can be understood, research reporting of onfarm trials was examined. The available data from onfarm trials show that the gap is not nearly as dramatic as implied by the above comparisons. Unfortunately, there are relatively few usable onfarm experimental data reported in the literature, despite the upsurge of "farming systems" research. Many research results are not reported, and when they are reported, they may be published and, hence, are difficult to obtain. The data reviewed and summarized in table 7 are highly scattered samplings, and they give quite a different picture than the experiment station trials reported above.

Onfarm trials were conducted at 26 locations in Veracruz State of Mexico from 1975-80, testing local and improved varieties at farmers' and higher input levels (table 7). The farmers' and improved varieties both yielded 2.0 tons per ha at farmers' input levels. At high inputs, the improved variety yielded 3.4 tons per ha, compared with 3.1 tons per ha for the farmers' varieties.

Similar trials at 418 sites in Ghana in 1982-83 (table 7) averaged 1.8 tons per ha with local maize varieties and farmers' inputs, compared with 3.0 tons per ha for the improved variety with an intermediate level of inputs (not reported in the table) and 3.5 tons per ha for the improved variety with a high level of inputs (34). In another set of trials, 74 sites in Ghana for over 3 years, the improved varieties averaged 3.9 tons per ha and the local farmers yielded 2.8 tons per ha when fertilizer and other inputs were held constant (table 7).

In Guatemala, the yields of improved maize varieties were compared with local varieties when grown with farmers' inputs and management at 7 sites in 1976 and at 16 sites in 1977-78. The improved varieties yielded 4.0 tons per ha, compared with 2.9 tons per ha for local varieties (34). In similar trials at 24 sites in Paraguay, improved varieties yielded 3.0 tons per ha, compared to 2.7 tons per ha for the local varieties.

Onfarm trials carried out by Haiti's agricultural department in cooperation with CIMMYT for the purpose of generating appropriate maize recommendations were reported in detail by Yates and Martinez (47). The experiments, conducted in three cycles between February 1981 and the end of 1983, gave results summarized in table 7. Treatments and input levels were adjusted from one cycle to the next by eliminating the less profitable alternatives. Cycle I was experiment station-type trials; cycle III was onfarm trials. In cycle I, the improved variety at high-input levels gave an increased yield of 0.5 ton per ha. In the second cycle, improved varieties with farmers' inputs and practices gave an increased yield of 0.1 ton per ha. With 80 kg per ha of applied fertilizer, the local variety yielded 2.9 tons per ha and the improved variety, 3.5 tons per ha. In the third cycle, yields of the improved variety were 0.2 tons per ha higher than farmers' varieties at farmers' input levels and 0.3 tons per ha higher than local varieties at high-fertilizer levels.

Cycle III experiments tested variety and nitrogen fertilizer; planting density, phosphorous fertilizer, and weed control had all been dropped because high levels of each could not be justified on the basis of their returns. Economic analysis of cycle III results showed that return to cash invested in fertilizer was quite good for landowners with both varieties of maize, but "fertilizer use in maize production is not economically available for sharecroppers".

Onfarm trials at 17 locations in Thailand showed that switching to an improved variety of maize with no fertilizer or other improved inputs increased yields by 0.1 ton per ha (49). By adding 50 kg per ha of N and 63 kg per ha of P_2O_5, yields increased only 0.4 ton per ha over fields not fertilized. Economic analysis showed that the cost of the fertilizer exceeded the value of additional production. Therefore profit was highest with the improved variety and other improved inputs.

Even where onfarm trials show that an alternative to farmer practice is profitable as well as higher yielding, there is still room to be misled. In many places, crops are grown as part of a system that requires one crop to be harvested before a second is planted. Yields normally increase with crop duration, but when another crop precedes or follows, farmers may prefer to sacrifice some yield and economic return from one crop in other to ensure profits from the other. Zeigler and Kayibigi recount such a case in which "improved" maize was not adopted in Burundi because "there may be a serious disadvantage to pursuing a selection strategy of maximizing maize yield with no regard for the other components of the system" (49).

It is obviously hazardous to generalize from such a small sample of experimental results. The onfarm trials reported in table 7 suggest that improved maize varieties may be expected to add no more than 1.0-ton-per-ha yield, and that improved varieties together with test levels of fertilizer and other inputs may add no more than 1.5 tons per ha in onfarm trials (table 7, yield increase 2). Economic analysis of the yield increases obtained from the high levels of fertilizer and other inputs often show that they are not profitable. That was the case for the trials in Haiti and Thailand. The relevant yield increase is, therefore, shown as yield increase (1) in table 7. These data support the hypothesis that there is little evidence of a large exploitable yield gap for maize.

Sorghum and Millet

High-yielding hybrid varieties of sorghum and millet were developed for the semiarid areas of India during the sixties. By the eighties, they had spread quite widely. These hybrids, like

Table 7--Performance of improved maize technology in onfarm trials

Location and number of trails	Level of variable inputs 1/			Yield	Yield increases3/		Source
	Variety	Fertilizer	Other inputs 2/		1	2	
				Tons per ha			
Mexico	F	F	F	2.0			(34)
26	T	F	F	2.0	-	-	
	F	T	T	3.1			
	T	T	T	3.4	0.3	1.4	
Ghana	F	F	F	1.8			(34)
418	F	F	F	3.5	-	1.7	
74	F	F	F	2.8			(34)
	T	F	F	3.9	1.1	-	(34)
Guatemala	F	F	F	2.9			(34)
23	T	F	F	4.0	1.1	-	
Paraguay	F	F	F	2.7			(34)
24	T	F	F	3.0	.3	-	
Haiti:							
I.1, 5	F	T	T	3.1			(34)
	T	T	T	3.6	.5	-	
I.2, 8	F	F	F	1.5			(47)
	F	T	T	2.5	-	1.0	
II, 4	F	F	F	2.3			(47)
	T	F	F	2.4	.1	-	
	F	T	F	2.9			
	T	T	F	3.5	.6	.8	
III.1, 8	F	F	F	2.1			(47)
	T	F	F	2.3	.2	-	
	F	T	F	2.6			
	T	T	F	2.9	.3	.8	
III.2,	F	F	F	1.1			(47)
	T	F	F	1.3	.2	-	
	F	T	F	1.8			
	T	T	F	2.1	.3	1.0	
Thailand	F	F	F	3.6			(18)
17	T	F	F	3.7	.1	-	
	T	F	T	4.0	-	.4	
	T	T	T	4.4	.4	.8	

1/ F = farmer's variety and level of inputs or low-added fertilizer;T = test variety or high level of inputs.
2/ Usually insect and weed control, often plant density.
3/ Yield increase in column 1 is the difference between the farmer' variety and experimental variety at fixed levels of fertilizer and other inputs. Yield increase in column 2 is the difference due to other inputs with variety held fixed.

semidwarf rice and wheat, were more highly responsive to fertilizer than were local varieties (35), and they apparently were attractive to many Indian farmers who adopted them.

By 1983-84, hybrid pearl millet covered 43 percent of the millet area and hybrid sorghum 29 percent of the sorghum area of India. In some producing areas, they spread even more rapidly--to 85 percent of the pearl millet area of Gujarat State and to 50 percent of the kharif (summer) sorghum area of Maharashtra. Only about 19 percent of the millet area and 12 percent of sorghum area were irrigated (45).

Analysis of the adoption of hybrid sorghum shows little use in areas where sorghum is mainly grown as a rabi (winter) crop. The adoption process seems to have been largely completed by the late seventies in the sense that adoption had reached a plateau, although at significantly less than 100 percent. Walker and Singh believe that to break these "ceilings" of adoption, second and third generation hybrids and varieties will have to be released (45).

These and other improved varieties and test lines from India have been widely tested in Africa but have not spread to the sorghum and millet producing areas of Africa. No statistical estimates exist, but two ICRISAT economists reported that probably less than 2 percent of total sorghum and millet area in west Africa is cultivars developed through modern genetic research (26).

This is true despite experiments in Burkina Faso that showed average yields with improved sorghum varieties of 1.9 tons per ha on the experiment station, compared with farmers' yields of 1.2 tons per ha. Improved millet yields were 1.3 tons per ha at the station, compared with 0.5 ton per ha for farmers' yields.

In a critical review of sorghum and millet improvement research, Matlon observered that some sorghum and millet varieties are acceptable in India and not acceptable in west Africa (26). Some of the reasons are: Most sorghum soils in west Africa have lower water-holding capacity and lower ion exchange capacity and as a consequence plant population must be lower. The rainy reason in west Africa lasts a shorter period even though it may provide as much rain. Extension support and infrastructure to supply chemicals is much less developed in west Africa. For these reasons, Matlon argues that varieties developed to give high yield with high inputs are inappropriate. New cultivars should be at least as tolerant or resistant to stresses (striga, downy mildew in millet, drought, sooty stripe, grain mold, and charcoal rot in sorghum) as local varieties, and they should provide a wider range of agronomic characteristics such as plant canopy or duration.

There must be development within Africa. Among 7,000 sorghum introductions screened by ICRISAT in Burkina Faso, 9 cultivars were found sufficiently promising in onstation trials to warrant onfarm tests. Of these, only two cultivars have been found to be generally superior under farmer's conditions. Among 3,000 millet entries screened, 5 cultivars advanced to onfarm tests, but no superior cultivars have yet been identified (25). A program to develop improved sorghum and millet varieties that will raise production and be acceptable to west African farmers is under way at the ICRISAT subcenter in Niger, but it will require some time to produce appropriate varieties.

Potential Medium-Term Productivity Increases

The discussion thus far has focused on potential for increasing production using technologies that can be examined at experiment stations although they are not widely used on farmers' fields. What is the future potential for developing still more productive technologies? Past yield gains have come through improving plants and the environment in which they are grown. A large share of the environmental improvement has been in the form of water and nutrient control that requires capital investment or current expenditures. Economic incentives to apply fertilizer nutrients, improve management, or invest in water control are interrelated with the capacity of plants to make productive use of the "improved environments," a capacity that is generated through plant breeding.

H. K. Jain has examined the record of wheat, rice, barley, and sorghum yield increases during the past 80 years of crop breeding (24). He concludes that most of the genetic basis for the observed yield gains have been achieved through redistribution of dry matter between vegetative and reproductive plant parts and that "there is little evidence to show that biological yield or the dry matter production has seen a significant increase during this period. Other authorities agree (12).

Jain observes that crops were selected over thousands of years to survive under stressful conditions. This process produced plants with high vegetative vigour and a minimum, but well assured, grain output. The deliberate effort of plant breeders to increase grain production has largely taken the form of increasing the ratio of output useful to man (such as, seeds in cereals) to total dry matter production, as illustrated in figures 10-13. This ratio, called the harvest index, it closely associated with plant height. Reducing plant height in the small grain crops has been the principal means by which harvest index and crop yield were raised,

Figure 10

Wheat in the United Kingdom

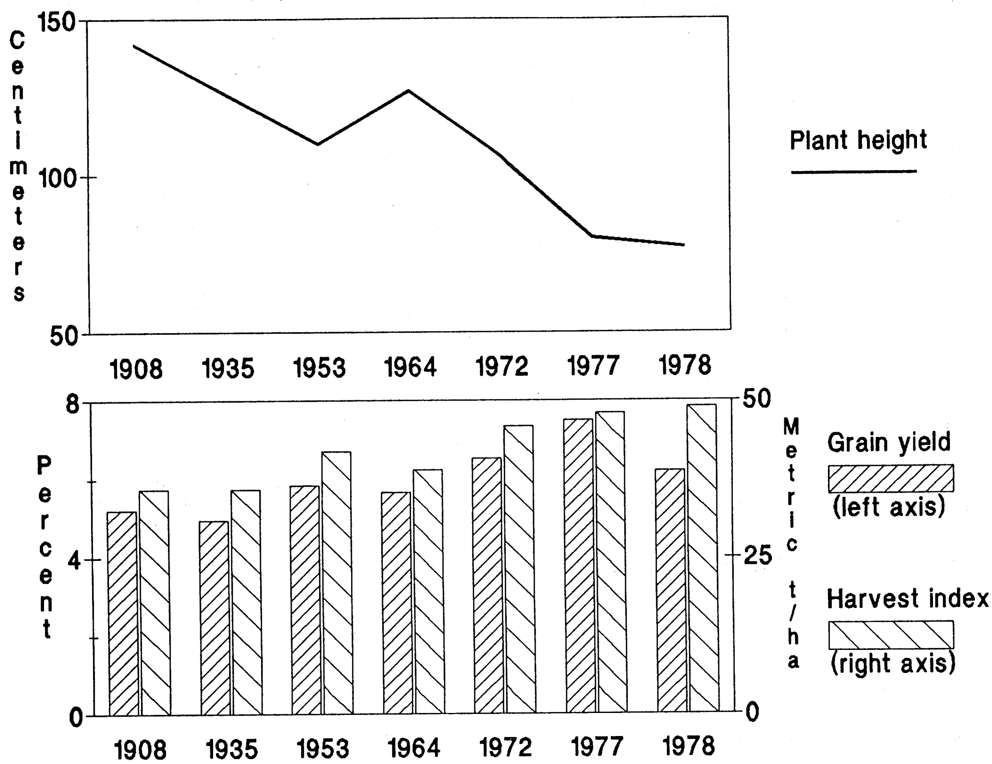


Figure 11

Wheat in India

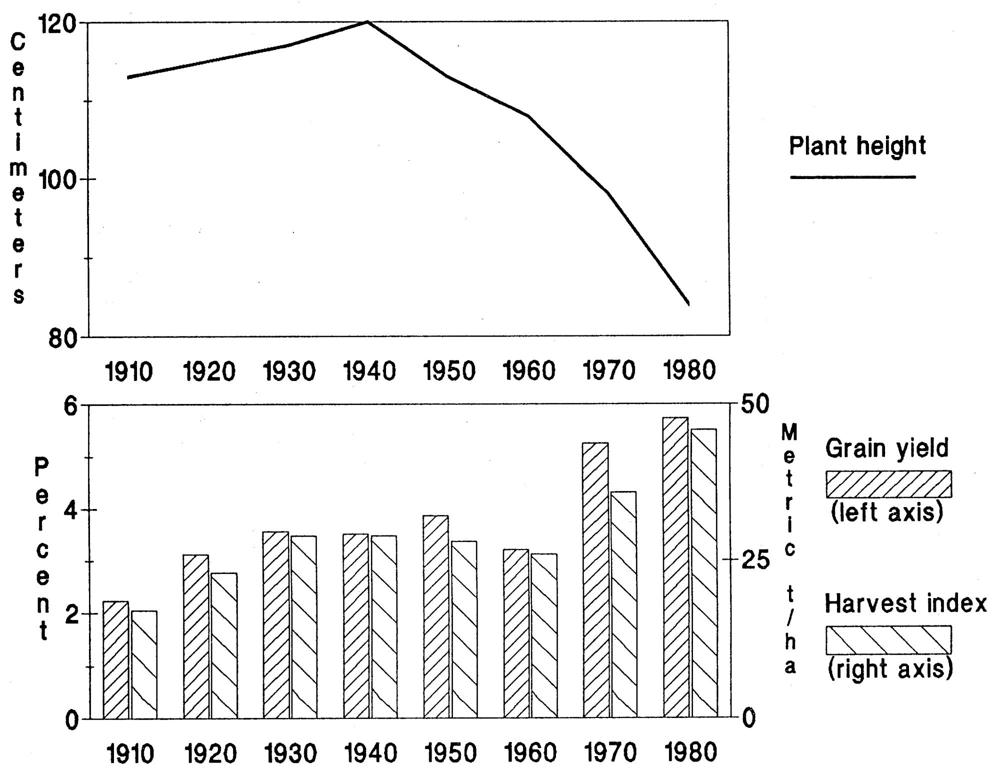


Figure 12
Sorghum in India

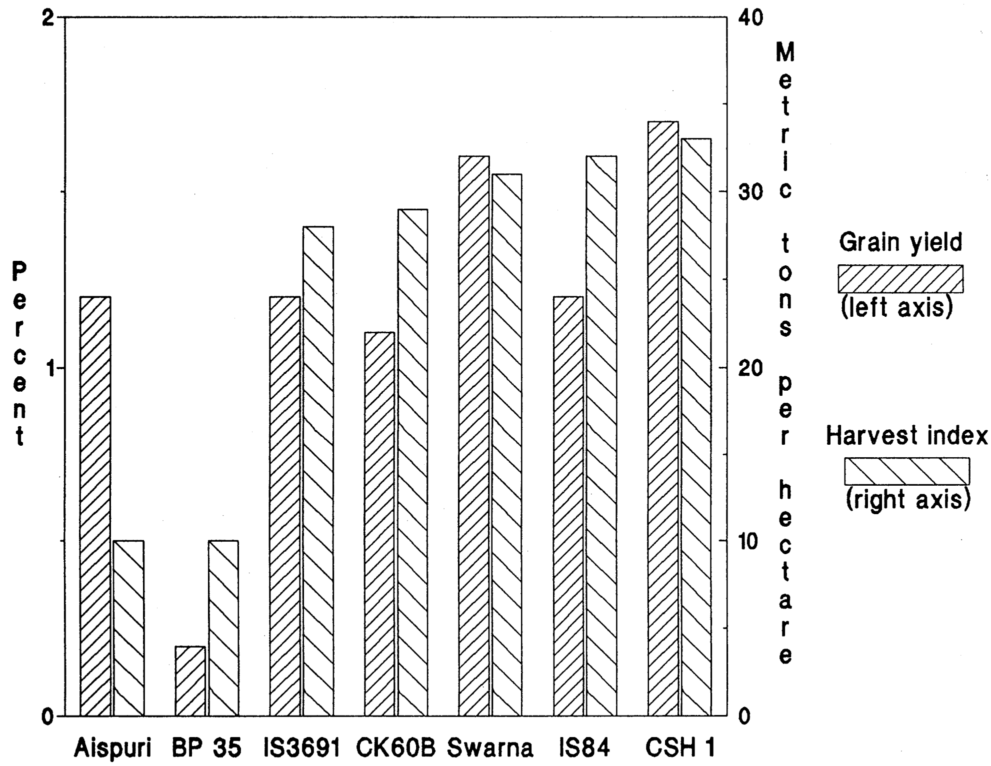
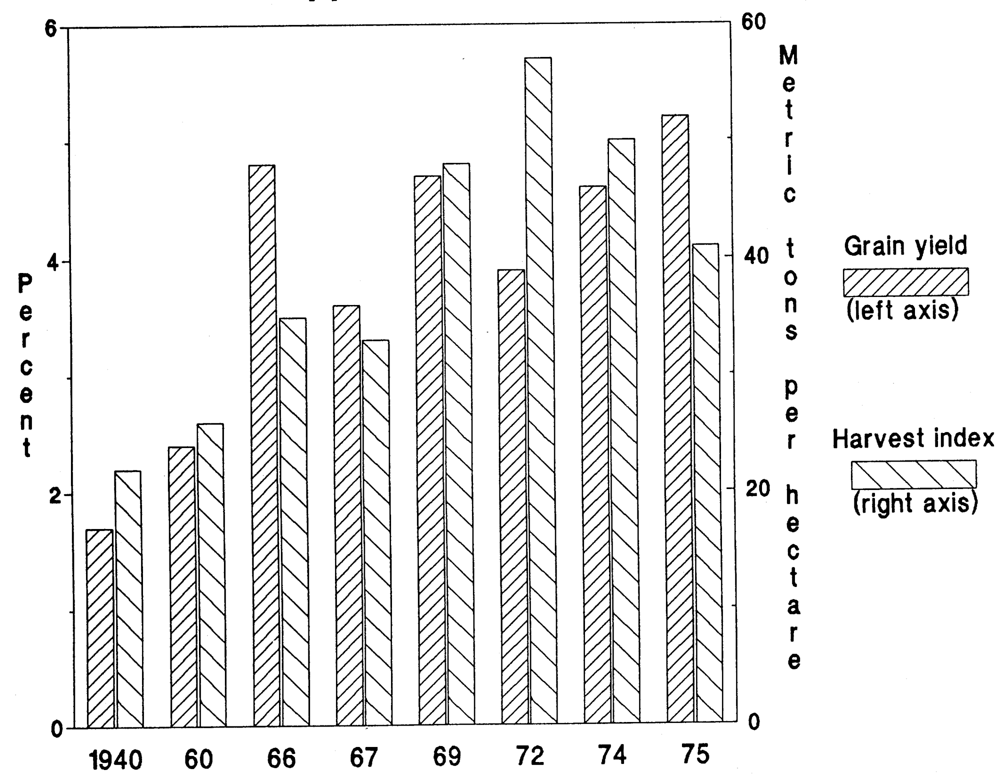


Figure 13
Rice in the Philippines



although maize seems to be different (11). The shortening process occurred gradually in the developed countries as illustrated for wheat varieties between 1908 and 1970 in the United Kingdom, but it occurred much more suddenly with the introduction of semidwarf varieties in the developing countries (wheat and sorghum in India and rice in the Philippines). The question facing agriculture in those countries is whether further scope exists for this kind of manipulation, and if not, what the source of future increases in yield potential will be.

Jain suggests that in developed countries some of the crops are beginning to reach yield plateaus. Citing other researchers from the United States and the United Kingdom, Jain concludes that the harvest index for wheat could possibly be further increased from its present level of 50 percent to 60 percent, after which total dry matter production (biomass) will have to be increased if grain yields are to be further increased. A similar conclusion might be warranted for developing countries that produce semidwarf rice and wheat. They have harvest index levels approaching 50 percent. The harvest index of improved sorghum and millet in India has reached about 30 percent, but as pointed out earlier no change has occurred in the commonly cultivated varieties in Africa.

The potential for improving maize yields in developing countries through genetics appears to be considerable, judging from advances made in the developed world. How quickly a similar improvment can be realized in the developing countries is difficult to judge, but I believe there is still some work to do.

An examination of yield trends of major crops in the developed world provides some indications of the inherent capacity of crops to respond to plant breeding. Table 8 shows such a comparison. Average grain yields in North America and Europe increased by a low of 70 percent for millet and a high of 307 percent for maize between 1948-52 and 1981-83, excluding rice in Europe which had a very high yield to begin with. Yield gains for other major crops seem to be somewhat less than for the major grains, although dry bean yields in Europe and peanut yields in North America increased over 160 percent. Soybean yields in Europe increased by nearly 96 percent, showing that yields of these crops have been increasing, but not quite as dramatically as yields of grains. In the developing regions, yields of most crops have increased much less, suggesting that there is genetic capacity for yield improvements if the appropriate research is done. The examples of millet and sorghum in west Africa and maize more generally show that there is no easy transfer of technology from one agricultural ecology to another, even when the ecologies appear to be similar. Research must be conducted in the agro-ecology for which the technology is intended.

Table 8--Major crops: Yields and yield changes in North America and Europe

Crop	North America			Europe		
	1948-52	1981-83	Percentage change	1948-52	1981-83	Percentage change
	Tons per hectare		Percent	Tons per hectare		Percent
Wheat	1.16	2.32	100	1.47	3.77	157
Maize	2.49	6.37	155	1.24	5.05	307
Rice paddy	2.56	5.26	105	4.27	5.07	19
Sorghum, millet	1.24	3.59	190	.85	1.45	70
Barley	1.45	2.69	85	1.68	3.41	103
Potatoes	15.58	29.17	87	13.78	19.02	38
Sweet potatoes	5.88	13.57	131	15.10	10.67	-30
Dry beans	1.19	1.58	33	.22	.58	166
Chickpeas	NA	NA	NA	.43	.58	36
Soybeans	1.43	1.96	37	.64	1.26	96
Peanuts, in shell	.94	2.49	164	NA	NA	NA

NA = Not available
Source: (13).

Summary and Conclusions

As the evidence suggests, there is relatively little under-utilized technology waiting for developing country farmers to adopt. Existing technologies, such as semidwarf wheat and rice, will spread further only at a modest pace. There is no apparent "breakthrough" just over the horizon. Maize, sorghum, and millet technologies, which would be substantial improvements over what exists, will take time to develop. Biotechnology's promise is somewhat uncertain, but it is clear that time will be required before that promise is at hand.

Research trials are misleading indications of absolute potential; their trends lead trends in farmer's production but a gap between the two is normal. Developing country farmers are responsive to opportunities offered by new technologies or changed economic conditions and rapidly adopt technologies that benefit them. Researchers are often mislead about what may be beneficial to farmers for a number of reasons: (1) they use inappropriate prices; (2) they fail to account for all costs facing farmers; (3) assume that farmers' production conditions are represented by experiment stations; and (4) they forget that reseachers normally maximize yields rather than optimize input levels. Thus, biological researchers tend to overestimate the advantage of new technologies compared with farmers' current practices.

Prices, and hence enforced price policies, can have significant effects on incentives to adopt new technologies, so it is conceivable that some technologies that are not sufficiently profitable to be attractive under current policies could be made somewhat more attractive. Policy changes cannot compensate for the lack of technical (yield) advantages, which appears to be the explanation for the difference between the observed rates of technical change for wheat and maize. Potentials for new technologies exist on every front, but all require further investment of research time and effort.

It seems to me that a faster, not a slower, rate of technical change will be needed to enable developing countries to keep domestic food production at a rate that will meet consumer needs and provide the basis for economic growth. Going beyond the data reviewed in this paper, I believe there is adequate basis for the following scenario. In the absence of technical change, agriculure in most developing countries will grow too slowly to permit adequate overall economic growth rates, which, in turn, will make it impossible for developing countries to import food for domestic consumption. On the other hand, if their agricultural sectors and incomes grow 3-4 percent per year, their food demand will probably outpace economic growth rates, making food imports necessary and feasible.

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