The Green Revolution

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The term "Green Revolution" was coined in 1968 by Dr. William S. Gaud, Director of the US Agency for International Development (USAID). This phrase immediately found widespread acceptance because of the dramatic impact of the semidwarf wheat varieties originating from the Rockefeller Foundation-Government of Mexico Program (the precursor of CIMMYT) and rice varieties originating from the International Rice Research Institute (IRRI). For example, in India wheat production rose from the previous high of 12 million tons in 1964 to over 17 million tons in 1968. The years 1965 and 1966 saw widespread drought on the Indian subcontinent. A potential famine of disastrous dimensions was averted in 1966 by the importation of nearly 10 million tons of wheat, most of which was supplied by the United States of America under its PL 480 program.

In his own inimitable style, Dr. Borlaug, whose name will find a permanent place in agricultural history for his role in triggering the wheat revolution in many developing countries, has already dealt with recent accomplishments in improving the productivity of maize and wheat. I do not therefore wish to repeat what he has said so effectively and elegantly. Instead, I wish to deal with some issues connected with the Green Revolution which have been in the forefront of public debate in recent years. I shall confine my discussion largely to wheat.

History of Some Past Agricultural Revolutions

The words "agricultural revolution" have been used to describe impressive progress in crop production in many parts of the world and at different times. The history of the agricultural revolution in Western Europe has been described by Grigg (1984) in a recent article. Another author has identified four stages in the British agricultural revolution. First, beginning in the 16th century, a shift took place from subsistence to commercial farming. Second, the introduction of new crop rotations as well as livestock improvement occurred early in the 19th century. Third, the period between 1820 and 1880 was characterized by the purchase by farmers of cattle feeds and artificial fertilizers and by investment in new buildings and drainage. The last stage, after 1914, saw the introduction of the tractor and of labor-saving machinery. Thus the English agricultural revolution that was thought to be a short and sharp break in the history of English farming has now been stretched to cover some 300 years. Because there was no precise definition of what an agricultural revolution implies, it has been described as the transition from traditional husbandry practices to modern scientific agriculture.

What triggers the transition from traditional practices to modern science-based agriculture? Historians of US agriculture say that hybrid maize which gave two to three times more yield than open-pollinated varieties triggered the change in the 1930s. Farmers who took to hybrid maize adopted improved management practices not only for maize but also for all the other crops they grew. Semidwarf wheat varieties originating from CIMMYT had the same impact in parts of India and Pakistan. For example, Punjabi farmers both in Pakistan and India, who started appreciating the value of improved nutrient supply and water management practices for semidwarf varieties of wheat, also extended improved management practices to rice, potato, and other crops included in the wheat farming system. Thus the area of the wheat revolution also became the area of the rice revolution, the potato revolution, etc. The role of catalysts of change in the attitude of farmers is obvious.

Progress in improving wheat yields between 1750 and 1980 in some countries of Western Europe is listed in Figure 1. The sharp increase in yield observed during the last 50 years in the countries included in Figure 1 is largely due to the unprecedented rise in the consumption of artificial fertilizers, the adoption of high-yielding cereal varieties, and control of pests, diseases, and weeds. There has been a sharp increase in labor productivity because of the fall in the labor force as a result of mechanization.

It is of interest that in several developing countries food output has increased even more rapidly than in Europe during the last 20 years. In spite of such spectacular progress, we should view the Green Revolution as just the first phase of a new era in tropical and subtropical agriculture.

I have spent some time going into history because some critics of the Green Revolution have tried to insinuate that the new technologies associated with the Green Revolution, such as the introduction of genetic strains of wheat and rice that respond well to good soil fertility and water management, have been specially designed to promote the commercial interests of multinational companies. Recent advances in Indian agriculture will illustrate how the Green Revolution in wheat and rice was really brought about by a series of evolutionary steps.

The Wheat Revolution in India

The period between 1947 when India became independent and 1966 saw three major evolutionary steps in agricultural planning and development. In the first phase, from 1947 to 1960, considerable emphasis was placed on the development of infrastructure such as rural roads, schools and hospitals, irrigation projects, and manufacture of mineral fertilizers. The second phase, from 1960 to 1965, saw the introduction of an intensive agricultural district program (IADP) which was designed to introduce a package of practices such as the cultivation of improved varieties and application of fertilizers and pesticides in areas with assured irrigation. The "package program," as it was popularly called, was introduced in areas with assured irrigation so that the benefits from water could be maximized. Unfortunately, the results during the first few years of this project were

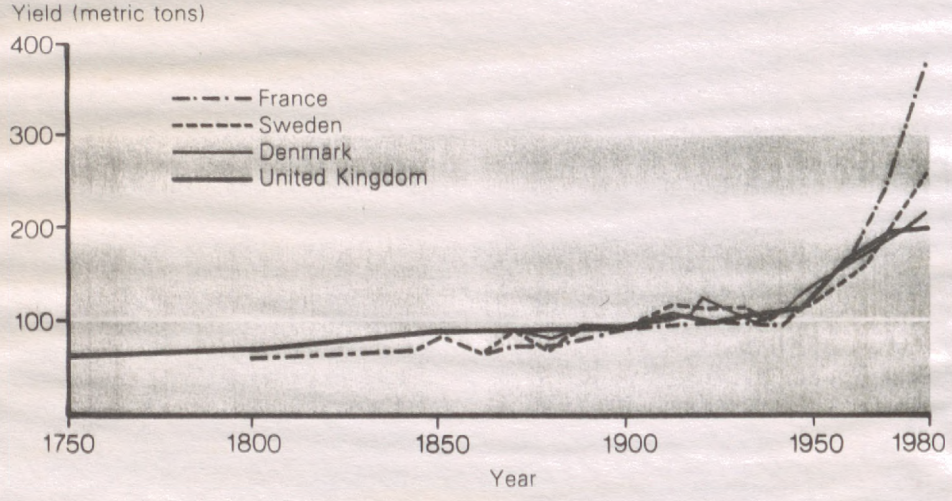

Figure 1. Wheat yields, 1750-1980.

Source: B.R. Mitchell (1975); Bennett (1935); Toutain (1961); FAO (1963, 1980).

disappointing because it was soon found that the "package" lacked genetic strains that could respond effectively to irrigation and fertilizer application.

This deficiency in the package program was resolved in 1966 when the high-yielding varieties program (HYVP) in wheat, rice, maize, sorghum, and pearl millet was introduced. The high-yielding wheat strains initially introduced under HYVP came from Mexico; in the case of rice some, like IR8, came from IRRI and others had been either developed locally or introduced from Taiwan. In the case of maize, sorghum, and millet, hybrids developed under the respective All India Coordinated Research Projects of the Indian Council of Agricultural Research (ICAR) were introduced.

The wheat revolution was the first to occur. There were several reasons for this. First, in the Punjab where the wheat revolution began, land consolidation and leveling, rural communication, and rural electrification had already made much progress before the new technology was introduced. In addition, Punjabi farmers were owners of the land, with the result that they had a long-term interest in the development of farm infrastructure. This is evident from the rapid growth in farmer-owned tubewell irrigation. Unfortunately, such preconditions for new technologies to take root and spread rapidly did not exist in many other parts of India. Hence, regional disparities in the spread of new technology became prominent. For example, the average yield of wheat was 3288 kg/ha in the Punjab, while it was 643 kg/ha in Karnataka during 1984-85.

The growth rate of wheat production in India between 1967-68 and 1980-81 was more than double the growth rate of production of all grains. The contribution of wheat to the total food grain production in the country increased from about 12% in 1966 to nearly 30% now. The 1985-86 wheat production is estimated to be around 46.5 to 47 million tons. Such spectacular progress would not have been possible if the government of India had not provided to farmers a remunerative price and assured marketing arrangements. Agriculture moves forward on a sustainable basis only when mutually reinforcing packages of technology, services, and public policies are introduced.

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Progress in Other Countries

Borlaug (1985) has described the progress made by several countries in improving wheat production. A few examples suffice to indicate the extent of progress made.

Pakistan, since 1966, has increased wheat production from about four million metric tons to over 13 million tons in 1983, an increase of more than threefold. Yields have more than doubled in the same period. Although Pakistan's rice production is only about one-fourth that of its wheat production, it has been a rice exporter for the last 12 years.

Turkey has more than doubled its wheat production in the last 10 years and has again become a modest exporter. Bangladesh, although still a small producer of wheat, has made spectacular progress in increasing production in the last five years, growing wheat after rice or jute.

The People's Republic of China has made striking progress in increasing cereal production during the past decade. It has long been the number one nation in rice production and ranks second only to the United States in maize production. In 1984, China harvested 87.8 million tons of wheat and thereby displaced the Soviet Union, which harvested 76 million tons, as the number one wheat producer in the

world. Most of the wheat grown in China is from winter varieties; however, the dwarf Mexican spring wheats have been used commercially in the south (along the eastern coast) where winters are less severe, and in the northeastern provinces (especially in Kirin), where they are sown in spring.

CIMMYT's annual reports during the past 15 years give an idea of the impressive progress made by nearly all wheat-growing developing countries.

Balance Sheet of Phase I of the Green Revolution

We can now draw a balance sheet of this first phase of the Green Revolution. First, a most important gain during this phase has been the generation of self-confidence in many developing countries with regard to their capability for achieving food self-sufficiency.

Second, agriculture has achieved a higher social prestige, and it is now widely realized that modern farming requires not only brawn but also brain (technology) and bank (financial and other resources). This realization has led to enhanced support for national agricultural research and extension systems and a greater flow of credit to the farm sector. Most political leaders now realize that a dynamic agricultural production program can neither be initiated nor sustained without the support of a dynamic national agricultural research system.

Third, the population-rich but land-hungry countries of South and Southeast Asia have been able to increase production through a vertical growth in productivity, thanks to the rapid spread of high-yielding varieties (Figure 2).

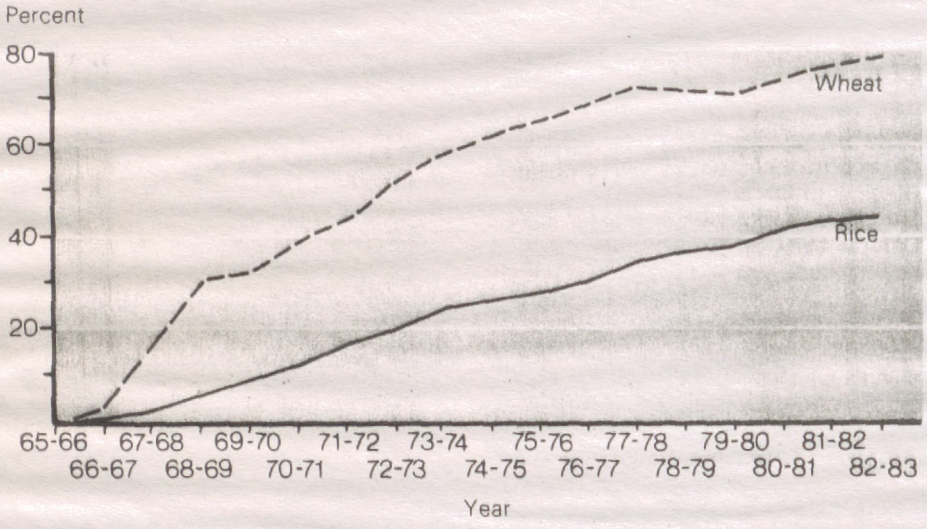

Figure 2. Estimated proportion of area planted to high-yielding varieties of wheat and rice, South and Southeast Asian nations, 1965-66 to 1982-83.

Source: Dalrymple (1985)

Fourth, a higher intensity of cropping could be achieved in irrigated and assured rainfall areas because of the availability of photoperiod-insensitive and short-duration varieties. For example, wheat acreage in Bangladesh expanded from about 120,000 ha in 1974 to more than 600,000 ha in 1984. All of the annual wheat crop in Bangladesh is planted in the winter season, starting in November, following the harvest of rice or jute. Altogether new rotations like rice-potato-wheat, cotton-wheat, and sugarcane-wheat became possible. Consequently, plant breeders have started making selections based on per-day rather than per-crop productivity.

Fifth, several developing countries could start building national food security systems based on the purchase of surplus home-grown wheat. India, which imported 10 million tons of wheat in 1966, had built a grain reserve of over 10 million tons by 1972 mainly with locally grown and purchased wheat. The government of India's grain stocks now exceed 30 million tons. These include the quantities needed both for food security and public distribution.

Finally, the old view that the illiterate farmers of India and other developing countries would not easily be able to take to new technologies has been disproved. Developing country farmers, whether literate or illiterate, have shown that they will readily adopt improved production techniques and high-yielding varieties if they are convinced that these new technologies will help to improve their income and standard of life.

Impact of the Green Revolution

What has been the impact of the Green Revolution on the principal members of the agricultural production team?

Impact on National Food Security

Wheat has become the anchor of the national food security systems of India, Pakistan, and several other developing countries. Hence, it will be useful to consider this relationship in some detail. Food security has been defined by the Food and Agricultural Organization (FAO) as "physical and economic access to food for all people at all times." This definition implies both adequacy of food supply and access to food for all human beings, irrespective of their economic status. In other words, food security requires integrated policies for production, distribution, and consumption.

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Progress in wheat production helped to destroy many myths and doomsday predictions. For example, it destroyed the myth that India can never feed itself (Paddock and Paddock, 1967). It destroyed the myth that agricultural evolution in developing countries has to be a very slow process and that revolutions in crop production are not easy because of the very large number of small-scale farmers whose active involvement is essential to make such revolutions possible. Thanks to the wheat revolution, India could start building a reliable national food security system.

Impact on Researchers

Research is a key component of the food production system. It determines to a considerable extent present levels of potential productivity and indicates the scope for raising further the production potential for the future. In addition to the prestige and self-confidence that agricultural scientists in developing countries gained following the introduction of high-yielding varieties, five more lasting benefits have been obtained.

First, the need for multidisciplinary research became obvious. Scientists began to appreciate the fact that purely discipline-centered research would not take them very far in improving the yield of crop plants. In India, soon after the

introduction of high-yielding wheat varieties, it became clear that several basic changes in agronomic techniques were essential for the new strains to reveal their full yield potential. Some of the changes were shallow sowing, application of first irrigation at the crown root initiation stage, split application of fertilizer, and efficient weed control.

If the political will exists, the pace of agricultural progress can be accelerated.

Second, scientists saw the advantage of multilocation testing to arrive at reliable conclusions more quickly. Even during 1963, the first year of introduction into India of four semidwarf wheat varieties from Mexico, the strains (Sonora 63, Sonora 64, Mayo 64, and Lerma Rojo 64-A) were tested at Delhi, Ludhiana, Pantnagar, Kanpur, Pusa, and Indore. The following year, the testing was done at many more locations using 250 tons of seed imported from Mexico. Based on two years' data from multilocation testing, the decision was made in 1966 to import 18,000 tons of seeds of Lerma Rojo 64-A and Sonora 64 from Mexico. Subsequent events have confirmed the wisdom of this decision.

Third, the wide adaptability of the Mexican semidwarf wheats revealed the value of shuttle breeding techniques involving diverse environments in the development of varieties with wide adaptation.

Fourth, exchange of genetic materials and their testing in international observation and yield nurseries permitted breeders everywhere to share the best available gene pool in the world. These nurseries also helped provide early warning on potential pest and disease problems.

Fifth, agricultural research managers realized that unless personnel policies were introduced to help attract and retain good scientists, it was not possible to meet the new challenges which constantly arise when agriculture starts moving forward. Policies that promote lifelong specialization by scientists became essential to build strong national research systems.

Impact on Extension Workers and Mass Media

Before the introduction of the high-yielding varieties program, extension workers in such countries as India had almost nothing to extend, either by way of new knowledge and skills or the inputs necessary for increasing production. The Green Revolution enhanced the prestige of extension workers and led to the synchronization of efforts to transfer knowledge and supply inputs. Furthermore, the feedback process between extension and research workers was strengthened and both groups started respecting each other.

Impact on Political Leaders

The Green Revolution showed that if the political will exists, the pace of agricultural progress can be accelerated. Since the population in most developing countries is predominantly rural and since agriculture is the major occupation of rural people, political leaders realized that they now had an opportunity to help improve the quality of life of the rural population. Consequently, agrarian reform and rural development measures started to receive greater attention at the political level.

Impact on Consumers

Consumers have probably derived the maximum benefit from the progress made during the last 20 years in the production of wheat and rice. This is because in low-income countries the bulk of adjustment to fluctuation in food supplies is made by the poor. I quote John Mellor's Foreword to International Food Policy Research Institute (IFPRI) Research Report No. 18 (1980):

> In low-income countries the bulk of adjustment to fluctuation in food supplies is made by the poor. The direct price and indirect employment effects of a 10% decline in foodgrain

supplies reduce foodgrain expenditure by as much as 40% in real terms for the lowest 10% of the income distribution. In contrast, with the same decline in production, the reduction in foodgrain expenditures is only 1% in real terms for the top 5% of the income distribution. And yet it is the poor who are least able to withstand such privation. The poor spend such a high proportion of their income on food that price increases induced by shortages greatly reduce their capacity to buy foodgrains, whereas the more well-to-do compensate by spending less on other goods and services, thereby further decreasing the income of the poor through reduced employment. Because the food intake of the poor is already so close to the minimum level, supply shortages result in increased malnutrition.

Thus one of the most important actions that can be taken to improve conditions for the poor is to reduce fluctuation in food prices and supplies.

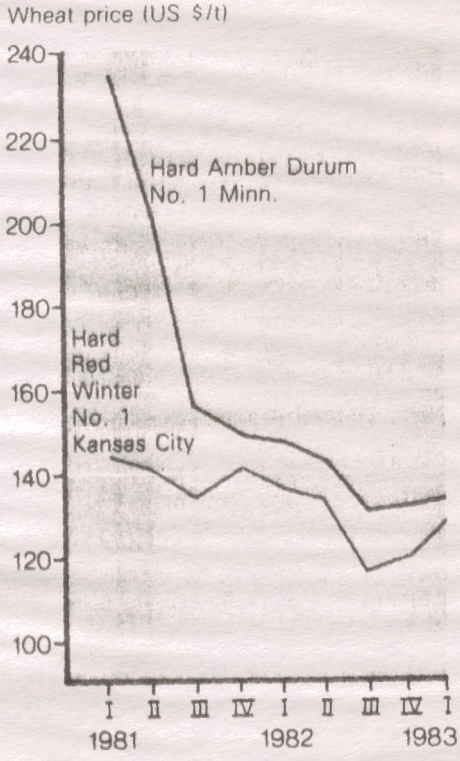

Figure 3. Wholesale prices of wheat in the United States, 1981-83.

International prices of wheat and rice are still declining, partly because of the large stocks in the world and partly because of the large subsidies being given to farmers in developed countries (Figure 3).

Literate or not, farmers are sound economists. To them, seeing is believing.

Impact on Farmers

Ultimately, it is farmers who decide what to grow and how to grow it, when to sow, how much to invest, and how to market their crop. All others can only support the farmers. In many countries of South and Southeast Asia, because of very small land holdings (average farm size ranges between 1 and 2 ha in countries like India), the active participation and assistance of a million farming families may be needed to produce an additional million tons of wheat or rice. Farmers have shown that they will readily take to new technologies provided they are convinced that such technologies will increase their income. Whether literate or illiterate, farmers are sound economists. To them, seeing is believing. This is why the National Demonstration Programme organized in India in 1964-65 and in later years was so very effective in convincing farmers that they were entering a new era in wheat yield. These demonstrations were laid out by scientists in the fields of small-scale farmers. The choice of small-scale farmers for organizing

demonstrations is important, because higher yields obtained by large-scale and affluent farmers will be attributed more to their financial status than to technology.

Today, farmers in both developing and developed countries face serious economic problems. Developing countries will have to organize appropriate social security systems for small-scale farmers if production is to be sustained at the needed level.

Phase II of the Green Revolution

While the positive gains have been many, there has been serious concern about the economic and ecological sustainability of the high-yield technologies associated with the Green Revolution. In addition, the accessability of new technologies to smallholders has also been questioned. Many of these doubts arose following the steep escalation from 1972 onwards in the price of inputs based on fossil fuel-derived feedstocks.

I would like to deal with a few of these issues. However, before going into detail it might be worthwhile to draw attention to the recent projections made by IFPRI on the food requirements of the Third World up to 2000 (Paulino, 1986). A trend scenario of the food situation in the year 2000 based on data from 1961 to 1980 for production and 1966 to 1980 for consumption projects a Third World production shortfall in basic food staples of about 70 million tons (76 million tons excluding China). This gap represents about 5% of the Third World's projected demand for basic food staples in the year 2000 and is one-third larger than the food deficit of developing countries in 1980. There is therefore no time to relax in our efforts to increase food production, to quote a favorite saying of Dr. Borlaug.

I shall deal with the emerging issues in three parts: first, those dealing with increased wheat production on a sustainable basis; second, those dealing with the economic well-being of wheat farming families; and finally, with increasing the consumption of wheat by the rural and urban poor. I shall conclude with describing some of the major scientific challenges that CIMMYT and national research systems will have to face in the coming decades.

Producing More Wheat

A popular misconception about high-yielding varieties of wheat and rice is that they cannot be grown without heavy inputs of fertilizers and pesticides. All the available data show that the semidwarf, high-yielding varieties of rice and wheat as well as sorghum hybrids can yield more than the old tall varieties at all levels of nitrogen application. This is because of the ability of the high-yielding varieties to partition more of their dry matter to the formation of grain (Figure 4). During this century, much of the progress in improving yields of wheat and other crops has come primarily from the improvement of the grain harvest index (Figure 5). While the per capita availability of arable land is going down in many Asian countries, the proportion of irrigated area is going up (Figure 6). Therefore, there is need for optimizing the benefits from water through synergetic interactions between nutrients and varieties. The relevance of high-yielding varieties will increase with expansion of irrigation and escalation in the cost of mineral fertilizers. In this context, the results of the work of CIMMYT in bringing about a continuous improvement in yield are of great importance (Figure 7).

Those who advocate going back to old varieties and old technologies, which were quite relevant when the pressure of population on land was low, will be

Table 1. Nitrogen (kg/ha) required for 4 t/ha grain yield with varying protein content

	Protein content (%)		
	12.5	13.75	15.0
Grains	80	88	96
Straw	20	29	32
Total	100	117	128

doing a great disservice to their countries by creating the impression that high yields can be obtained with varieties that are inefficient in the utilization of nutrients. The nutrient requirements for a 4 t/ha wheat crop at three different protein levels are given in Table 1. The international prices are very much influenced by protein content and grain quality (Figure 8). Therefore, the supply of adequate nutrients is essential for improving yield and quality. What can be done, however, is the partial replacement of mineral fertilizers with farm-grown biofertilizers. Green manure crops such as the stem-nodulating *Sesbania rostrata*

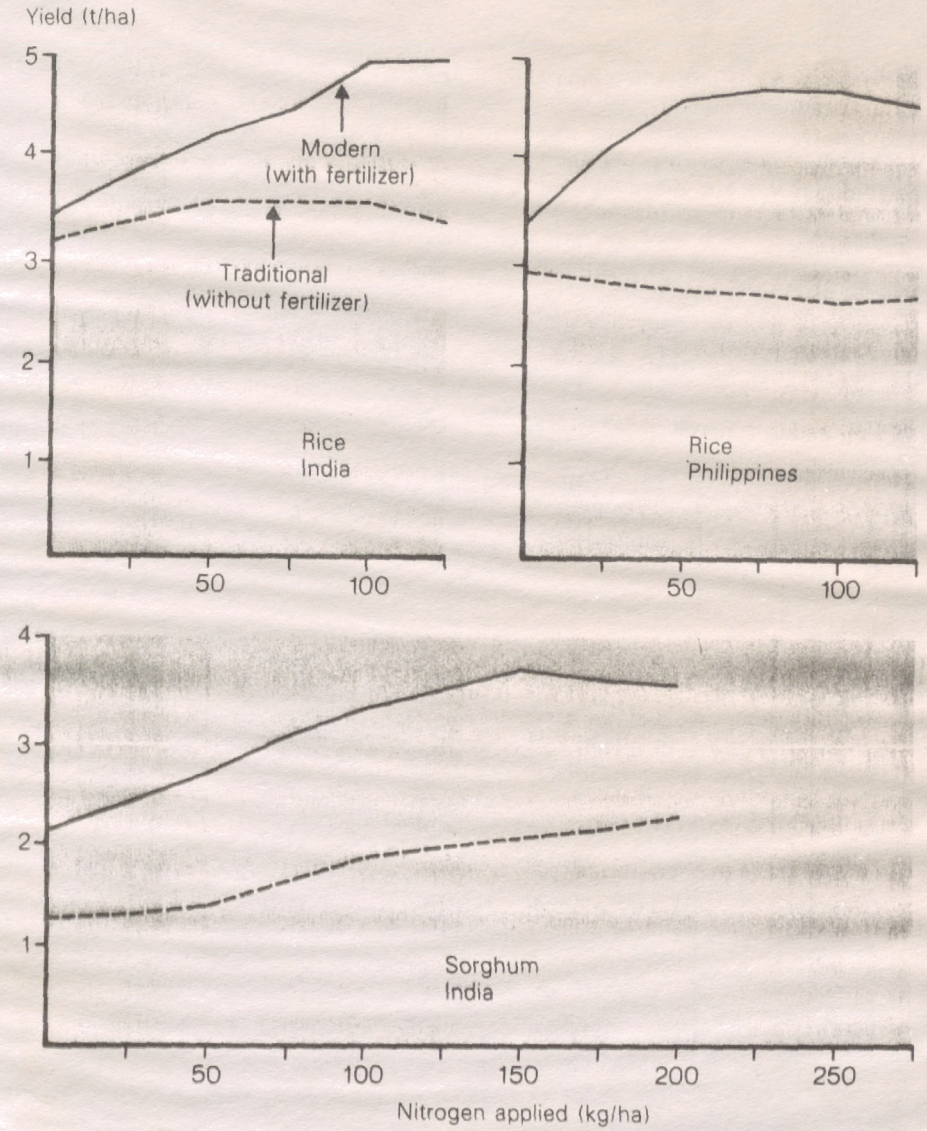

Figure 4. Yields of rice and sorghum with and without fertilizers.

Source: CGIAR (1985)

deserve greater attention (IRRI, 1986). Most of the high-yielding varieties have built-in resistance to a broad spectrum of pests and pathogens. In fact, the ready acceptance of semidwarf wheat varieties received from Mexico in India in 1964-65 was in part due to their resistance to most of the races of leaf and stripe rusts which were then important.

To develop a strategy for further increasing production, the following eight items deserve attention.

1. Characterizing environments and tailoring varieties and management techniques to specific growing conditions—To derive full benefit from a given environment, detailed work will have to be done along the lines of the analyses indicated in Tables 2 to 6 with regard to different wheat ecologies in India. The production constraints and research needs indicated in Tables 2 to 6 are neither complete nor comprehensive, but they illustrate the kind of detailed work required for determining research priorities and strategies.

Fortunately, recent advances in genetic engineering provide an opportunity for transferring genes across sexual barriers and for producing new recombinants. Wheat scientists should derive maximum benefit from the new opportunities now open for generating variability through tissue culture and genetic engineering techniques (Swaminathan, 1986). Recently it has been shown that the bacterial chloramphenicol acetyltransferase (CAT) gene can express itself in protoplasts of wheat (Ou-Lee, Turgeon, and Wu, 1986). In Canada, a

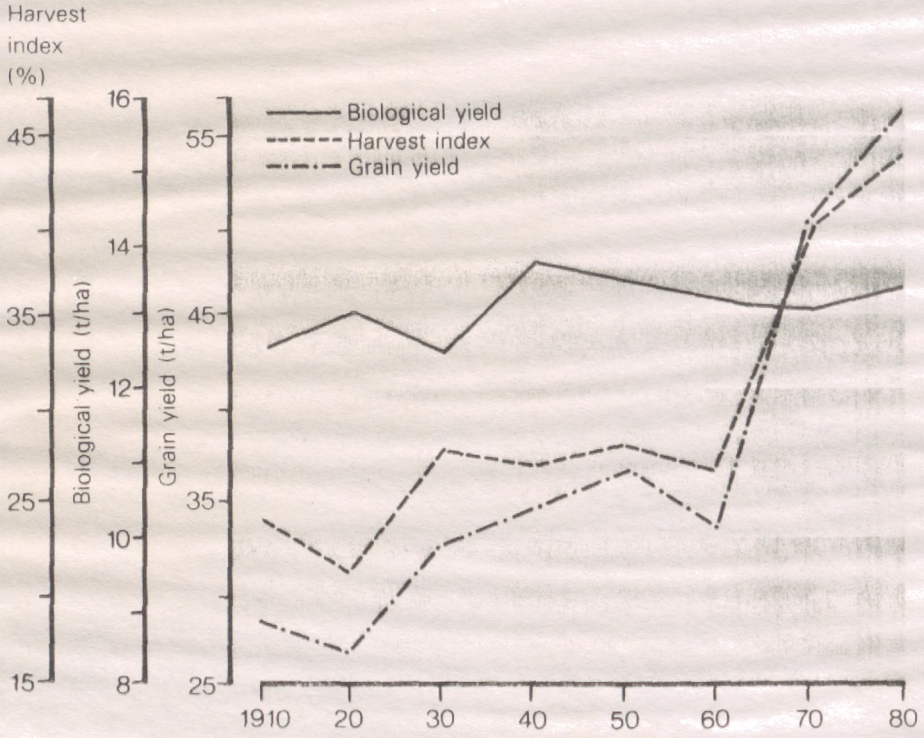

Figure 5. Trend of varietal grain yield in relation to its two parameters, 1910 to 1980.

Source: Kulshrestha and Jain (1983)

high plant regeneration efficiency has been reported from immature embryos of Neepawa, a widely cultivated wheat variety.

2. Improvement of durum wheats—A major effort is needed to improve durum wheats (*Triticum turgidum* var. *durum*). Ethiopia, considered to be a center of origin of wheat, has a climate similar to that of peninsular India. The wheats of this region until recent years were almost all tetraploids, mostly durum and emmer. The essential absence of hexaploid wheats suggests that durum wheats are more adapted to higher temperatures than are bread wheats (*Triticum aestivum*). The durum wheats have a large mass of awns relative to total spike mass. This is helpful, because at higher temperatures the photosynthesis system of awns relative to leaves is more stable. At higher temperatures the rate of grain filling in durum wheats is much higher than in bread wheats. In view of these adaptations, tetraploid wheats must be screened with greater vigor for cultivation in central India. The disease and lodging susceptibility of earlier durum wheats is no longer a serious problem with the availability of disease-resistant and semidwarf varieties. Durum wheat can be improved further by incorporating genes for disease resistance from wild relatives as well as from *T. aestivum*. We also need to enrich our germplasm base by collecting durum wheat lines from early cultivation areas.

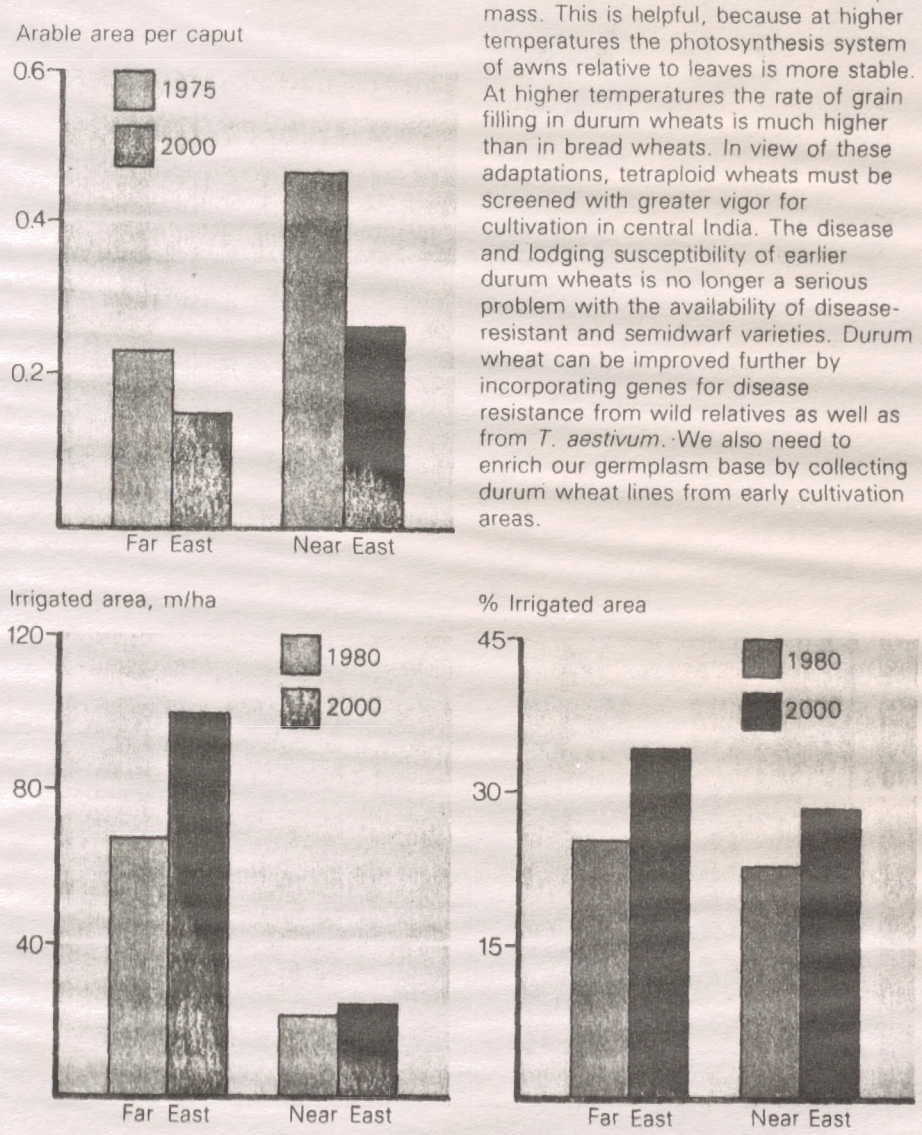

Figure 6. Proportion of irrigated area, Far and Near East.

Source: FAO

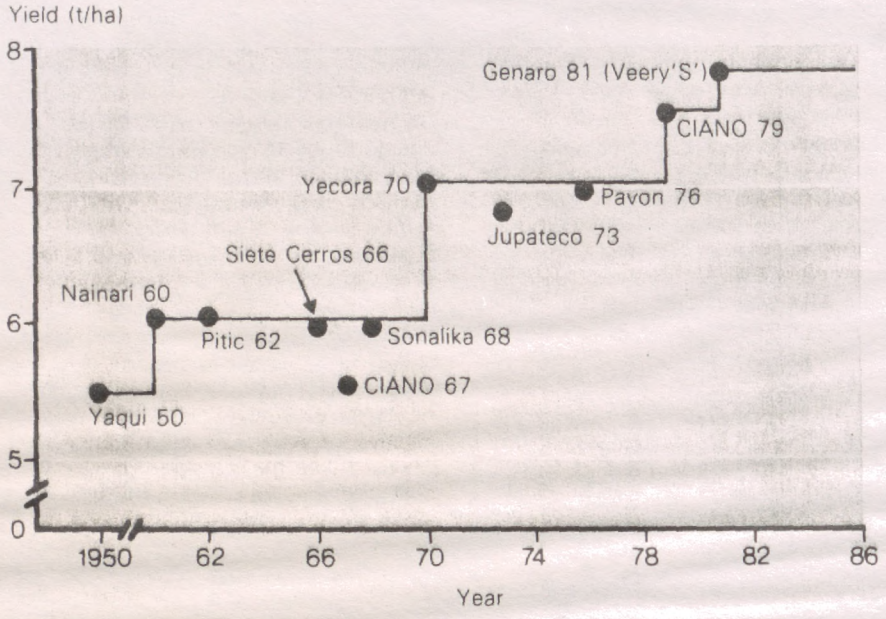

Figure 7. Average yield of Mexican varieties under favorable management conditions.

Source: CIMMYT

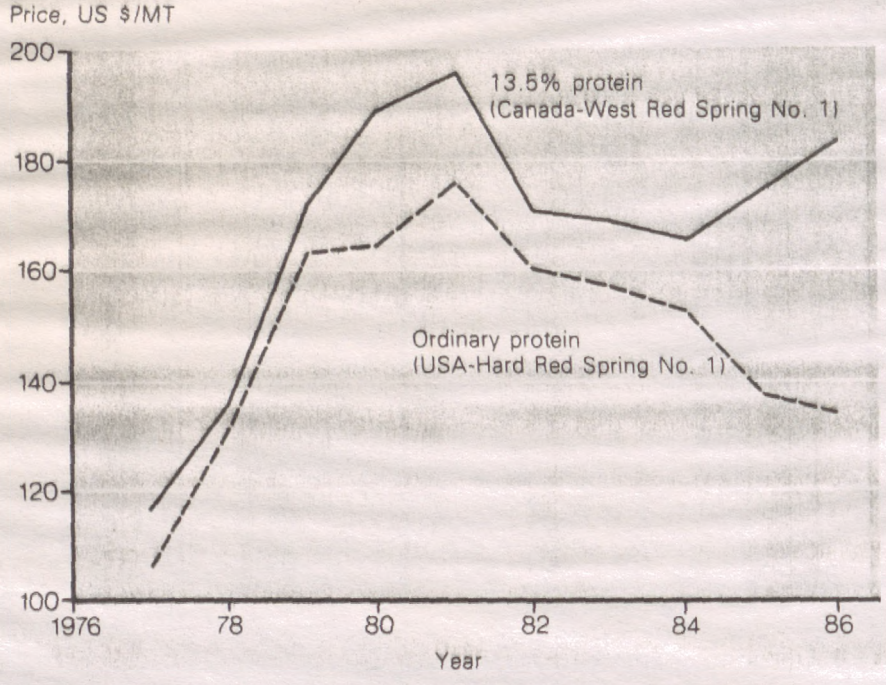

Figure 8. International prices as influenced by protein content and grain quality.

There is considerable variation in protein content of durum wheats. Studies at the University of Nebraska indicated a range of 7.3% to 21.7% with a mean of 12.75% and SD of 2.86%. The lysine content also varied from 0.29% to 0.59%. It should be possible then to breed for higher protein content. Quite frequently, an increase in protein content leads to a calorie penalty. Hence, great care should be taken not to lose grain yield potential while breeding for higher protein content. The bread-making quality of hexaploids is regulated by the D-genome. Selective incorporation in durum wheats of the D-genome's quality-related chromosomes such as 1D may help to improve bread-making quality of durum wheat grain. The recent techniques of chromosome and genetic engineering may help in developing new recombinants (Payne, 1986).

3. Soil and water care—Nature has endowed many Asian countries with good soils and ample water resources. The water resources are increasingly being harnessed for irrigation. In the last few years, the area under irrigated wheat has greatly expanded. In the Punjab and Haryana States of India, practically the entire wheat area is now under irrigation. However, this resource is not being utilized efficiently. The easy availability of irrigation water has often led to over-irrigation, resulting in increased problems of waterlogging, salinity, and alkalinity (Table 7). The magnitude of these

Table 2. Wheat production constraints and research needs, Northwest Region of India

Problem	Possible solution
Sowing gets delayed—yield is reduced	Develop short-duration varieties with high yield potential
	Increase heat tolerance at grain filling
	Increase resistance to rusts
Increasing problems of waterlogging, salinity, and alkalinity	Improve water management systems (particularly drainage)
	Breed for tolerance to salinity
Micronutrient deficiencies	Increase the use of farmyard manure
	Promote balanced fertilization
Grain quality	Increase nutrient uptake efficiency
	Genetic engineering
Raising yield potential	Improve dry matter production
	Examine scope for fixation of heterosis through anther culture and genetic engineering
Weeds: wild oats and *Phalaris minor*	Adopt suitable rotations
	Weed control measures

problems can be considerably reduced by improving the on-farm management of water as well as the drainage system. The alternative approach is to develop salt-tolerant varieties. There is thus an increasing need to identify genes, if any, for salt tolerance in wheat and related plants.

Table 3. Wheat production constraints and research needs, Central Region of India

Problem	Possible solution
Low yield despite increased irrigation	Synergy in input use—increase fertilizer use and area under high-yielding varieties
Short duration	Develop photosensitive wheats with durable resistance to rusts
	Increase heat tolerance
Unstable yields due to drought	Improve moisture conservation
	Evolve isogenic lines of varieties varying in root length
	Winter x spring wheats
Low yields of durums	Enrich germplasm base and develop high-yielding varieties
	Breed for resistance to stem, leaf, and stripe rusts

Table 4. Wheat production constraints and research needs, Eastern Region of India

Problem	Possible solution
High temperature	Develop short-duration varieties with high yield potential
	Increase tolerance to high temperatures
Poor crop stand due to heavy-textured rice soils	Develop simple machines and implements for tillage and seeding
Problem saline soils	Improve drainage
	Reclamation measures
	Develop salt-tolerant varieties
Low input use	Increase distribution of credit
Alternaria and *Helminthosporium* spp. diseases	Breed resistant varieties
Good quality seed	Develop storage methods to keep seed dry

Intensive cropping also leads to soil erosion and consequent loss in native fertility. Although such soil degradation problems are not of recent origin, exploitative agriculture may accelerate the pace of damage to soil health. Therefore, we need to develop cropping practices such as minimum tillage to check the valuable loss of soil resources. Continuous cropping and high productivity levels also result in soil exhaustion, particularly of micronutrients. There are increasing reports of zinc, iron, manganese, sulfur, and copper deficiencies in areas of intensive agriculture. Many of these problems are in part due to decreased organic matter in the soil and can be rectified to some extent by increased use of farmyard manure. It will also be important to use fertilizers with an optimal nutrient balance.

Table 5. Wheat production constraints and research needs, Western Region of India

Problem	Possible solution
High temperature	Increase heat tolerance
	Develop photosensitive varieties with durable rust resistance
Low plant population	Use higher seeding rates and varieties with fewer tillers
	Intercrop with adapted crops

Table 6. Wheat production constraints and research needs, Southern Region of India

Problem	Possible solution
Very high temperature	Select alternate crops
Stem rust and other disease problems	Develop resistant strains for cultivation in the Nilgiri hills

Table 7. Annual increase in waterlogging and soil salinity in some irrigation projects in India (000 ha)

Project	State	Waterlogging	Salinity
Gandak	Bihar and Uttar Pradesh	3.50	36.40
Ukai-Kakrapan	Gujarat	0.63	0.32
Mahi-Kadana	Gujarat and Rajasthan	3.90	1.70
Chambal	Madhya Pradesh and Rajasthan	7.59	3.08
Tawa	Madhya Pradesh	-	1.11
Rajasthan Canal	Rajasthan	3.92	2.65
Sarda Sahayak	Uttar Pradesh	5.72	0.94
Ramganga	Uttar Pradesh	27.90	50.40

Source: Joshi and Agnihotri. 1984. Indian Journal of Agricultural Economics, v.39.

4. Plant health—Eternal vigilance is the price of stable agriculture. In particular, constant vigilance is needed to guard against damage to the crop by pathogens, pests, and weeds. Joshi, Singh, and Srivastava (1986) have described how certain diseases which were not important before have now become important in the wheat crop in India and vice versa. For example, Karnal bunt (*Neovossia indica*) of wheat has now become important in northwestern India, although until recently it was considered to be a disease of minor importance. Research on methods of achieving stable resistance through such approaches as multiline breeding, cultivation of diverse genetic strains thereby avoiding genetic homogeneity, and breeding for horizontal resistance needs to be stepped up. At the same time, disease monitoring and surveillance systems should be given adequate support. This is where the international observation and yield nurseries distributed by CIMMYT assume particular significance.

5. Increase in protein content—We have four options available to increase protein content:

- Introduce genes for higher protein content into desired lines by conventional breeding or genetic engineering;
- Increase the partitioning of nitrogen (N) in favor of grains (increased nitrogen harvest index, utilization efficiency);
- Increase the amount of N fertilizer applied; and
- Increase the uptake of soil nitrogen (uptake efficiency).

The final grain yield and protein content of a wheat grain represents the result of a number of physiological and biological processes occurring over the growth period. The level of protein can be increased if more nitrogen is made available for plant uptake. By providing unchanged nitrogen availability, protein yield can be increased by either improved nitrogen uptake from the soil (uptake efficiency) or by increased mobilization of nitrogen from vegetative organs to the grain (utilization efficiency). A grain yield of 4 t/ha with a protein content of 12.5% needs 100 kg N/ha to be harvested by the crop (assuming 75% nitrogen harvest index). If the same yield is needed with 15% protein, then the crop will need to scavenge from the soil at least 128 kg N/ha. Alternatively, the nitrogen harvest index will have to increase from 75% to 96%. The latter might not be practical since it is likely to induce rapid breakdown of leaf proteins and increase the rate of leaf senescence, thus reducing the grain yield. Therefore, breeding for increased utilization efficiency does not appear to be practical. However, screening can be done for increased uptake efficiency. To some extent, genetic variability is available for this character. Cropping practices that minimize nutrient losses should also be standardized.

6. Increased efficiency of farming systems—In Bangladesh, Pakistan, and northern India, rice-wheat rotation has become predominant. The two crops appear to be complementary for optimum use of soil resources since rice derives its nutrients largely from the surface layers whereas wheat has a much larger feeding zone. Compacting light-textured soils for rice in the monsoon season might also be advantageous to wheat in terms of water and nutrient retention. Despite this complementarity, wheat yield after rice is generally lower than after maize. We have to find out the reasons and identify solutions. The possible reasons may include rice crop residues, plow pan, turnaround time, tillage, seedbed preparation, and delayed rice harvest. All of these factors will lead to the delay in sowing time of wheat. This will expose the crop at the grain-filling stage to higher temperatures, which are known to reduce yield (Figures 9 and 10). Therefore, it is necessary to develop varieties having tolerance to higher temperatures at the grain-filling stage. There is also a need to breed rice varieties characterized by a high per-day productivity which will enable the planting of wheat at the optimum time.

We have to reorient breeding programs to meet the needs of an entire cropping system, rather than of only one crop in the rotation.

Screening for low-maintenance respiration might be a good approach. This has been used successfully in soybean and ryegrass, and therefore it should be possible to select for low maintenance respiration rates in wheat as well. Pubescence of leaves and other deposits on leaf epidermis are additional mechanisms by which leaf temperature can be reduced. Since awns have a higher temperature optimum for photosynthesis, selection for larger awn mass may be helpful. Heat shock proteins have recently been identified in many crop plants. Thermotolerance is the proposed function of these proteins. We will have to study if these can be characterized and incorporated in breeding lines without changing their yield potential. Physiologists and breeders need to work more closely to screen both genetic stocks and segregating material.

In view of the increasing pressure on land for supporting an ever growing population, we will have to design efficient land use plans. Crop rotations will have to receive greater attention based on both national needs and soil productivity maintenance. These plans have to be ecologically sustainable and economically viable.

7. Resistance to preharvest sprouting—In the last couple of years, unseasonal rainfall in northern India in April and May resulted in a considerable loss in grain quality. Often grains germinate in the spikes. The projected delay in wheat sowings and harvest may further increase the probability of grain being affected by rainfall at the time of maturity. Therefore, it is desirable to develop lines resistant to sprouting.

The phenomenon of sprouting in the spikes is a complex process involving a number of steps. Many of these are affected by the environment. Two main

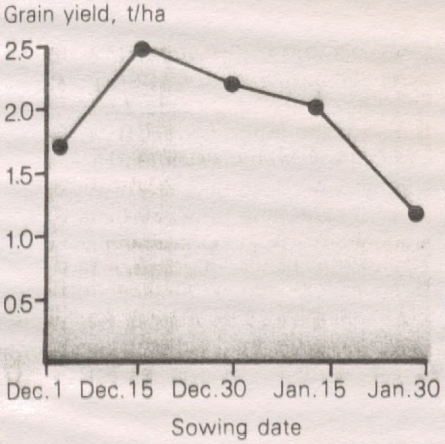

Figure 9. Response of wheat to dates of sowing in Los Baños (14°N), Philippines.

Source: Aggarwal *et. al.* (1986)

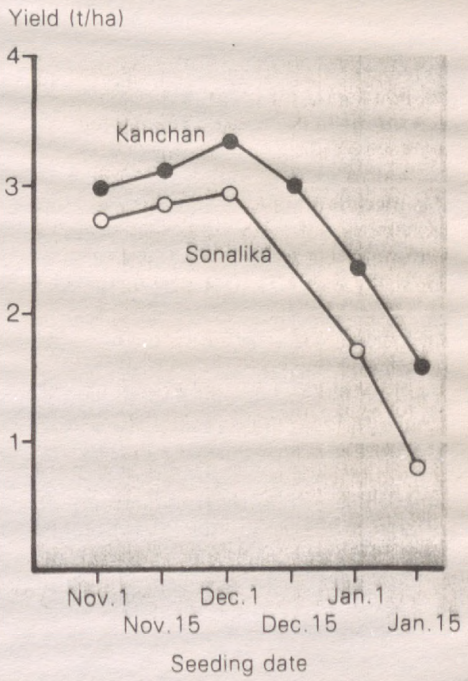

Figure 10. Yield response of Kanchan and Sonalika at six planting dates in Bangladesh.

Source: Butler, L. (personal communication)

groups of alpha-amylase isozymes are related with sprouting. The two isozymes appear to be under independent genetic control. There exists substantial genetic variability with respect to susceptibility to sprouting. A thorough screening of wild relatives might lead to the further identification of useful gene donors. In the future, we will have to know more about the physiological mechanisms, particularly in relation to phytohormones, that regulate the basic metabolic events in the sprouting process. Simple but reliable analytical tools need to be developed that would enable breeders to rapidly screen large numbers of materials.

8. Improved postharvest technology— The moisture content of wheat grain is a critical factor from harvest until its processing. Wheat can be safely stored for a few months only if the moisture content is below 14%. Therefore, it is necessary to develop small-scale grain driers based on solar energy and crop residues. It is equally important to develop energy-efficient and yet economical systems for large-scale storage of buffer stocks. Sometimes water seeps into the storage vessels, leading to the sprouting of the seeds. We therefore need to incorporate short-term labile dormancy in wheat seeds. Fortunately, considerable genetic variability exists for this trait.

Increasing Income of Wheat Farmers

It will be difficult for developing countries to give farmers prices that will necessitate heavy subsidies at the consumer level because of the vast dimensions of the undernutrition problem in most of these countries. On the other hand, the net "take-home income" of farmers with 2 ha or less land remains very low, so we should develop a strategy for improving the income of wheat farmers. Some components of the strategy are:

- Production cost should be reduced without reducing yield. For example, research designed to promote farm-grown substitutes for market-purchased chemicals like fertilizer and pesticides will have to be stepped up.

- Wheat farming systems should be so designed that maximum sustainable income can be obtained from the available land, water, labor, and credit resources. In this context, the rice-wheat rotation of northwestern and eastern India, Pakistan, and Bangladesh, as well as cotton-wheat, potato-wheat, and other crop rotations that are possible under irrigation, will have to be developed in such a way that all crops in the rotation can perform in a physiologically efficient manner. We need more research on wheat farming systems to improve the efficiency of the system as a whole.

- Research and development efforts in biomass utilization need to be strengthened. For example, a wide array of value-added products can be prepared now from straw, leaves, and grains. Studies by Munck and Rexen in Denmark (1986) have shown that there is considerable variation in the chemical characteristics of the straw. One interesting finding is that some of the plant samples have a high production of both starch and cellulose measured as yield per hectare. Studies at several institutions in India have shown that the quality of wheat straw can be further improved through treatments with anhydrous ammonia and fertilizer-grade urea. It is important that the new opportunities now available for preparing value-added products from every part of the wheat plant are studied carefully, and suitable choices are made based on marketing opportunities.

Stimulating Consumption

Some developing countries like India have built up substantial wheat and rice reserves at a heavy cost. Unfortunately, the availability of surplus wheat and rice in India is rather skewed in terms of geographical spread. Heavy transport costs are involved in moving grain from surplus to deficit areas.

Krishna and Chhibber (1983) have constructed models for determining the needs of the public distribution system in India in good and unfavorable crop years. Government stocks are steadily increasing and storage losses compound the financial burden arising from capital immobilization. Whatever the cost, the quantities of grain needed for maintaining a food security reserve and for operating an effective public distribution system will have to be stored. What can governments do with the balance?

A desirable solution to this dilemma is the planned use of wheat as cash to meet a part of the wage component of labor in development projects. Policies should be developed for integrating cash and grain while preparing the budget for development projects. In other words, we have to move one step further from the "Food for Work" approach and develop policies and procedures for using home-grown surplus grain as an important budget resource. Grain quality control will be essential if such an approach is to find acceptance among those who receive grain instead of cash. Ezekiel (1984) has shown how India's grain surplus, far from being a problem, provides an opportunity for overcoming the twin challenges of hunger and unemployment.

To sum up, Phase II of the Green Revolution will need for its sustenance and success a blend of knowledge, intensive technologies, and biological and chemical inputs. We can say that the first phase of the Green Revolution, starting in 1966 and ending in 1986, has helped to disprove the prophets of doom and gloom, and has led to the birth among developing nations of a new confidence in their agricultural capabilities. We are now entering the next phase where new problems will have to be faced and solved.

First, we need to step up our research and training efforts, which can help increase and stabilize the production of wheat, maize, and other crops, and improve the economic well-being of small-scale farmers through diversified employment opportunities resulting in the generation of greater household income.

Second, we should try to raise further the ceiling to yield under irrigated conditions. In this context, there is a revival of interest in hybrid wheat. Knudson (1986) has summarized the state of the art in relation to hybrid wheat development. A major factor will be the commercial viability of hybrid wheat technology. According to Knudson (1986), to produce the same amount of seed, approximately twice as much land is needed for hybrid wheat seed production (10,125 ha) as for conventional wheat seed programs (15,265 ha). Further studies alone can show whether hybrid wheat is likely to become a commercial reality.

The barrier between poverty and relative prosperity can be removed more through the application of science and technology than through any other means.

The various factors involved in increasing crop productivity are summarized in papers presented at "An International Conference on Crop Productivity—Research Imperatives Revisited" held in Michigan in 1985. From a strictly biological point of view, it may be possible to increase the yield potential of wheat further if the total biological yield can be increased by distant hybridization followed by efficient partitioning of the total dry matter. In our legitimate desire to increase yield, we should not sacrifice resistance to pests and diseases. Stability of production is equally important. In this context, the role of genetic engineering techniques needs careful analysis.

Finally, the Green Revolution in developing countries essentially has been a public sector enterprise. The era of "gene revolution," which looms large on

the horizon because of advances in molecular genetics, is predominantly a private sector enterprise in the developed world. The rapid spread of Green Revolution technologies became possible because the research results were disseminated with the sole motivation of helping farmers to increase production. Emerging technologies associated with the broad area of biotechnology may provide opportunities for adding a dimension of resource neutrality to scale neutrality in technology development. Will these new opportunities become available to small-scale farmers in developing countries in the same way as the Green Revolution technologies in the 1960s? It is in this context that the role of CIMMYT as a nonprofit, nonpolitical, autonomous scientific organization becomes so important for developing countries. Through its collaborative arrangements with similar advanced institutions, CIMMYT can help in the speedy transfer of the benefits of the latest tools of science and technology to the national research systems of the Third World.

While I have dealt only with wheat in this paper because of my personal involvement in wheat research and production over the past 30 years, CIMMYT's work on maize has been equally praiseworthy. According to the Consultative Group on International Agricultural Research (CGIAR) Impact Study Team, maize varieties derived from CIMMYT material cover six million hectares in over 15 countries. CIMMYT's Tuxpeño group of maize lines has been notable for disease resistance. The incorporation of resistance to streak virus in some new maize materials by the International Institute of Tropical Agriculture (IITA) has deservedly been recognized through the award of the King Baudouin Prize for 1986 by the CGIAR.

The wall that separates people living in poverty from those who enjoy relative prosperity can be removed more through the application of science and technology than through any other means. CIMMYT, by bringing to Third World farmers the best that mission-oriented multidisciplinary team research can produce, has contributed to improving the well-being of numerous rural families in the tropics and subtropics.

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