International Wheat Breeding and Future Wheat Productivity in Developing Countries

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Abstract: International wheat breeding for developing countries has been marked by a predominance of public sector research, multilateral exchange of wheat germplasm, and notable success in the widespread diffusion of modern wheat varieties in the developing world. Since the Green Revolution, wheat yields have grown much faster in developing countries than in developed nations. Between the mid-1960s and 1980, however, net wheat imports by most developing countries increased rapidly. Since 1980 aggregate net imports have stabilized, almost entirely because of higher production levels in three large producers, China, India, and Argentina. Wheat yield growth is slowing in developing countries, partly because varietal replacement is now more important than initial adoption, but perhaps also because of environmental factors. Future challenges for wheat breeding in developing countries include maintaining the level of investment in the international system, adapting to greater use of intellectual property in genetic material, and overcoming environmental constraints to intensified wheat production.

Keywords: wheat, plant breeding, wheat yields, wheat consumption, wheat imports, research investment.

Introduction

Today, developing countries (not including transitional economies of Eastern Europe or the former Soviet Union) produce just under half of the world's wheat, on half of the total harvested area devoted to wheat. Developing countries' share of world wheat consumption is even higher, at slightly under 60 percent, implying that as a whole, the developing countries function as a net wheat importer. Over the last 40 years, production and yields of wheat in developing countries have grown faster than they have in high-income countries. Today, average wheat yields in developing countries are about the same as the world average, above yields in Eastern Europe and the former Soviet Union, but slightly below yields in high-income countries.

Much of the initial growth in developing country wheat production has come as a result of technological change, known loosely as the "Green Revolution." The Green Revolution was based on the introduction and diffusion of high-yielding, short statured wheat varieties that were more responsive to fertilizer. Shorter wheat with greater stalk strength permitted higher rates of fertilizer application without lodging. Irrigated wheat area also increased, particularly in Asia.

The new varieties at the center of the Green Revolution were the product of an international wheat breeding network that included national agricultural research systems (NARS) and the International Maize and Wheat Improvement Center (CIMMYT), which was founded in 1966 and grew out of an earlier Rockefeller Foundation program in Mexico. Since the Green Revolution, this wheat breeding system has continued to develop new wheat varieties. In the post-Green Revolution period, wheat breeders have continued to improve yield potential, stress resistance, and input use efficiency. In other words, wheat varieties released today in developing countries are in general superior to the original Green Revolution varieties (Evans and Fischer 1999). In the first post-Green Revolution period, total factor productivity in wheat production (as measured primarily in India) grew even faster than it did in the immediate Green Revolution era. More recently, however, both total factor produc-

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tivity (TFP) and yield growth have slowed in the most intensely cultivated irrigated wheat areas (Rejesus, Heisey, and Smale, 1999); declining land quality has been observed in some of these areas (Ali and Byerlee 2001); the level of future investments in international wheat improvement has become more uncertain (Heisey, Lantican, and Dubin 2002); and public wheat breeders in both high income and developing countries have expressed concern over the effects of greater intellectual property protection on plant breeding (Kronstad 1996).

This article begins with a history of the international wheat breeding system. The paper outlines the current structure of this system and makes a rough estimate of resources devoted to wheat breeding for developing countries. The paper then summarizes the diffusion of high-yielding, semidwarf wheat varieties in the developing world. The final section assesses recent changes in the system, and briefly discusses some of the challenges it faces.

Throughout the report the world's wheat breeding and production areas will be divided into three major areas. "High-income" or developed countries, whose recent (1996-2000) wheat production ranged from 205-220 million metric tons annually, will include wheat producers such as the United States, Canada, Australia, and the European Union. Countries of the former Soviet Union and Eastern Europe, in which recent annual wheat production was about 90-115 million metric tons, will be designated "transitional economies." "Developing countries" make up the rest of the world, with annual wheat production of about 270-285 million metric tons. These divisions attempt to take into account political and economic realities, which are subject to change, as well as environmental factors that affect wheat production.

The Development of International Wheat Breeding Efforts

Perhaps more than for any other major world crop, modern wheat varieties are based on genetic material from many parts of the world. Germplasm from developing countries has been used to improve the varieties grown in high-income countries, and germplasm from high-income countries and transitional economies has been used to improve varieties planted in developing countries (Smale et al. 1996; Pardey et al. 1996). Although the ancient zones of origin of wheat were in Mesopotamia, wheat spread east and west from these zones very early. Wheat was cultivated in many parts of Eurasia and North Africa by 3000 B.C. and reached China by the second millennium B.C. (Harlan 1987). More recent diffusion of wheat can be described as "colonial" wheat germplasm flows, which began about 1500 A.D. (Smale and McBride 1996).

Modern scientific plant breeding can trace its development to cereal hybridization or planned cross-breeding which began in England in the 1790s and continued there through the work of Sherriff in the mid-19th century. The last decades of the 19th century were marked by greater interest in both cross-breeding and better methods of selection in Europe, North America, and Australia. Wheat improvement began to take the form of crossing locally adapted material with wheat from other areas in an effort to improve production characteristics or quality (Lupton 1987). The rediscovery of Mendel's laws of heredity at the turn of the 20th century led to renewed interest in using genetics to improve crops.

The narrow economics of plant breeding—defined by the costs of achieving a given objective by alternative means—have been marked by a tradeoff between working with the germplasm most suited for the target area and acquiring genetic material from outside to address problems that cannot be solved within the basic gene pool. Using traditional plant breeding methods, the genetically more distinct the source plant population for a desired trait is from the target plant population, the higher the costs of incorporating that trait into the target population. The success of a modern plant breeding program depends, among other things, on access to a large pool of germplasm agronomically suited to the target area, ability to tap new genetic resources as the need arises, and the capacity to recombine large amounts of genetic material and efficiently evaluate the resulting progeny over a wide variety of conditions. The cost of a plant breeding program is reduced to the extent that it can rely on other institutions to store and test genetic resources, and incorporate these resources into agronomically adapted material. These technical factors help to explain the historical path of plant breeding in developing countries.

The advent of scientific plant breeding in areas of the world characterized as "developing" probably began in India in the first decade of the 20th century (Jain and Byerlee 1999). Research stations with the aim of wheat improvement were founded in Turkey in the 1920s and the 1930s, and planned crosses were made in Argentina and Brazil in the 1930s. Although some crossing was done in China as early as the 1920s, it was not until the 1950s that planned crossing began to replace selection from landraces[2] as the primary means of wheat improvement. Introduction of foreign germplasm into China also became more prominent in the 1950s (Dalrymple 1986; Smale and McBride 1996; Yang and Smale 1996; He and Rajaram 1997).

The evolution of the modern system of wheat improvement in the developing world has often been linked to the Green Revolution. The Green Revolution had its origins in the transfer of semidwarf wheat varieties developed by the Rockefeller Foundation research program in Mexico to India and Pakistan. This initial transfer was followed by the establishment of CIMMYT in Mexico in 1966 as the successor to the Rockefeller Foundation program. Countries that already had wheat improvement programs reorganized and expanded them, and countries without wheat research programs began to develop them. The pace of interchange of wheat germplasm between NARS and CIMMYT and among NARS accelerated. International nursery activity became a major feature of the international wheat breeding effort, and visits of wheat scientists to CIMMYT and other countries also grew rapidly (Dalrymple 1986; Byerlee and Moya 1993; Maredia and Byerlee 1999; Smale and McBride 1996; Skovmand *et al.* 1995; Smale *et al.* 1996). Although China also participated in NARS-CIMMYT interchange, wheat-growing environments in China differ somewhat from those originally targeted by the rest of the international system. The international system originally primarily targeted low latitude spring wheat environments (70 percent of the total wheat area in developing countries, or 85 percent if China is excluded), while over half the Chinese wheat area was winter wheat. Chinese breeders developed many of their modern varieties independently of the international system.

In high-income countries much wheat breeding has also remained within the public sector, especially in Australia, Canada, and the United States. As with developing countries, the public wheat breeding system developed with an emphasis on germplasm exchange among different research institutions (Kronstad 1996). Wheat germplasm flows also continued between high income and developing countries. This is in contrast to corn, where the innovation of hybrid varieties led to technical means of intellectual property protection through inbred line development, encouraged widespread private sector investment in corn breeding, and resulted in fewer direct germplasm exchanges among distinct breeding programs.

In the case of wheat, factors such as plant varietal protection, the role of wheat within the cropping system, and level of wheat yields affected incentives for private companies to invest in wheat breeding. Private sector wheat breeding was practiced in Western Europe from the early 20th century and accelerated since the mid-1960s. Today 70 percent or more of the European Union wheat area is planted to private varieties. In comparison with other high-income wheat producers, European Union wheat production is technically higher yielding, and high subsidies in the European Union encourage more input use and yield-enhancing investment. Intellectual property rights applied to plant breeding have also had a longer history in Europe. Private varieties are less common in the United States, Canada, and Australia, but institutional developments such as research funding through farmer check-offs, or the strengthening of intellectual property rights in plant breeding, continue to influence the organization of wheat breeding in these countries (Heisey, Srinivasan, and Thirtle 2001).

In developing countries, private sector wheat breeding has a long history in the Southern Cone of South America, particularly in Argentina. Outside of the Southern Cone, the only countries where private sector wheat breeding is currently important are South Africa and Zimbabwe. With the partial exception of South Africa, private breeders in developing countries make extensive use of genetic material developed by the international public sector wheat breeding system (Heisey, Lantican, and Dubin 2002). Developing countries that have notable levels of private sector wheat breeding investment are usually characterized by the presence of large-scale commercial farmers in wheat production. The early introduction of intellectual property rights for plants in Argentina also played a role.

The wheat areas of Eastern Europe and the former Soviet Union have played an interesting role within the international wheat breeding system. These areas have been a major source of wheat germplasm for the world. Furthermore, in the 1920s, the Russian scientist N.I. Vavilov was the foremost explorer of plant genetic resources for a variety of crops. But for both historical and technical reasons transfer of genetic material from the currently "transitional economies" to developing countries has been indirect for the most part. For example, the related winter landraces Turkey and Turkey Red, which originated in the Crimea, appear in many pedigrees of spring bread wheat varieties that are grown

[2] Landraces are usually varieties developed in traditional agriculture by many years of farmer selection. They are not the result of planned crosses between two distinct breeding lines.

in developing countries. But the first commercial spring bread wheat variety in the developing world that descended from Turkey was probably five generations removed from Turkey, and resulted from the use of many other genetic sources as well (Smale and McBride 1996).[3] In the early 1970s, CIMMYT began to incorporate winter habit germplasm, much of it from the Soviet Union, into the spring wheat gene pool. The Soviet variety Kavkaz (which descended from the widely used Soviet variety Bezostaya on both sides of the pedigree) was an important ancestor of many of the spring bread wheats grown in developing countries today.[4] As the economies of the countries of the former Soviet Union contracted, plant breeding in those countries has also faced increasingly severe resource constraints. CIMMYT began collaborating with countries of Central Asia and the Caucasus in the mid-1990s and opened a regional office in Kazakhstan in 1998.

To cross winter with spring varieties using traditional breeding methods, as in the examples just cited, requires environments where the winter wheat can be planted at a time that its growth cycle will pass through temperatures cold enough that it will vernalize, enabling it to flower later, but the spring variety can be planted at a time that it will not be subject to winter kill. Flowering of the two varieties must also be synchronized. CIMMYT has locations in the highlands of Mexico where such crossing is possible. Day length considerations also affect the manner in which higher latitude wheat germplasm, of both winter and spring habit, can be incorporated into wheat varieties planted at the lower latitudes more typical of much developing country production.

In summary, the global wheat improvement system consists of both national and international public sector wheat improvement programs and private sector firms. Exchange of genetic material among different wheat research programs has been commonplace, but environmental considerations have influenced the ways in which germplasm with different genetic backgrounds has been combined. Over time and space, public sector programs have provided the majority of wheat varieties grown, although private sector breeding programs have become increasingly important in Europe and, to a more limited extent, in the United States. Public sector wheat breeding continues to provide the vast majority of wheat varieties planted in developing countries.

Wheat Production in Developing Countries and the Structure of Wheat Breeding Programs

Since the breakup of the Soviet Union, the two largest wheat producers in the developing world, China and India, are now the two largest single country producers in the world. Argentina, the fifth largest wheat producer in the developing world in most years from 1996 to 2000 (after China, India, Turkey, and Pakistan), is one of the major world wheat exporters. Wheat area and production in China, India, and Argentina, as well as other world regions, are summarized in the second and third columns of table C-1. After China and India, developing country wheat production is largest in the Middle East (including North Africa),[5] where roughly 50 million metric tons of wheat are produced annually. Turkey is the largest producer in this group of countries. Latin America and Asia, excluding China and India, each produce roughly 20 million metric tons annually, with Argentina being the largest producer in Latin America and Pakistan the largest producer in Asia after China and India. Relatively little wheat is produced in Sub-Saharan Africa.

Because of the importance of growth habit and day length in shaping conventional breeding possibilities, it is important to distinguish growth habit from time of planting in characterizing major wheat growing environments around the world. Spring bread wheat is the dominant type of wheat grown in developing countries, although at the low latitudes characteristic of many of the wheat growing environments in these countries, it is usually planted in the fall to take advantage of cooler growing conditions. Facultative[6] and winter habit

[3] Along some branches of the pedigree, the path that Turkey followed passed through both the U.S. and Japan.

[4] CIMMYT probably obtained Soviet germplasm from the country of Turkey, which in turn had received it from the former Yugoslavia.

[5] Within the international agricultural research system, the Middle East and North Africa are usually referred to as West Asia/North Africa, or WANA.

[6] Facultative wheats are intermediate in growth habit between winter and spring types. They possess fewer of the major genes for vernalization than winter types. They are usually planted in the fall, but in somewhat warmer environments (e.g. parts of the U.S. Pacific Northwest, central and southern Texas) than environments in which winter wheats are grown (e.g. Kansas), although the growing environments may overlap. A good variety with some facultative characteristics such as Jagger is sometimes planted in colder environments, although winterhardiness, which is often linked with the vernalization characteristics, may be an important factor in farmers' planting decisions.

Table C-1--Wheat production and imports in developing countries

Country/region	Average wheat area, 1996-2000	Average wheat production, 1996-2000	Major wheat types (percent wheat area)	Percent wheat area irrigated or high rainfall	Imports as a percent of total consumption, 1996-2000	Imports from U.S., 1999-2000
	(m ha)	(m mt)				(m mt)
China	29.1	111.9	W bread, 56% S bread, 44%	85	1	0.2
India	26.5	68.9	S bread, ≈100%	87	1	--
Other Asia (not including West Asia)	10.2	21.4	S bread, 100%	74	S Asia 18% E, SE Asia 99%	1.1 6.3
Middle East (West Asia/ North Africa)	26.9	47.9	S bread, 44% W bread, 31% S durum, 21%	47	37	6.6
Argentina	6.1	15.0	S bread, ≈100%	48	major exporter	--
Other Latin America/ Caribbean	3.3	8.2	S bread, 79%	94	68	5.8
Sub-Saharan Africa	2.8	4.9	S bread, 65%	60	58	2.4

Note: S=spring habit wheat. W=winter or facultative habit wheat.

Sources: USDA-ERS; Wheat Situation and Outlook Yearbook, March 2001; FAO; International Maize and Wheat Improvement Center (CIMMYT) Wheat Impacts Data Base, 1997.

wheats are very important in China, and winter wheat is also important in the Middle East, particularly in Turkey and Iran. Outside of these regions, facultative or winter wheats are grown in South Africa and parts of southern South America. Because growing areas often overlap, facultative and winter wheats are often grouped together as "winter" wheat, and the rest of this article will follow that convention.[7] Durum wheat is also important in the Middle East. Outside of the Middle East, durum wheat is grown in Ethiopia, parts of Latin America, and to a relatively minor degree in India (fourth column, table C-1).

Much of the wheat grown in China and South Asia is grown under irrigated or high rainfall conditions. In general, outside of China and South Asia less wheat area is irrigated or high rainfall (fifth column, table C-1).[8] Some of the irrigated/high rainfall wheat area is subject to other non-biological stresses such as heat, cold, or acid soil conditions. Much of the world's wheat area, including that situated in developing countries, is subject to biological stresses, particularly wheat rusts, which are fungal diseases.

As noted, both national and international wheat breeding efforts attempt to increase wheat yield potential and overcome both biotic and abiotic stresses. It is very difficult to get accurate estimates of the resources devoted to wheat breeding worldwide. In the 1990s, investment in wheat breeding research across all developing countries was estimated to fall somewhere between $110 and $170 million (1996 U.S. dollars) annually. This figure consists primarily of public sector investment. In addition, wheat breeding expenditures at CIMMYT and elsewhere in the international public research system were estimated from $10 to $15 million (1996 U.S. dollars) each year (Heisey,

[7] Failure to distinguish growth habit from time of planting can lead to considerable confusion. For example, official statistics for China call all wheat planted in the fall "winter" wheat. This provides useful marketing information, but it is less useful from a breeding perspective. In fact, some of China's "winter" wheat area is planted to pure winter varieties, much is planted to facultative habit varieties, and some is planted to spring habit wheat planted in the fall (He and Rajaram 1997).

[8] Much of the "irrigated/high rainfall" wheat area in China and South Asia actually receives some irrigation water. In Latin America, in contrast, most of the "irrigated/high rainfall" wheat area is high rainfall, with the exception of northwest Mexico, where considerable wheat area is irrigated.

Lantican, and Dubin 2002). As a point of comparison, in roughly the same time period, wheat breeding investment in the United States was estimated at about $50 million annually. Investment in the U.K. was around $20 million each year, and in Canada, Australia, and Germany annual wheat breeding expenditures were estimated to fall between $10 and $12 million (Heisey, Srinivasan, and Thirtle 2001).

Although CIMMYT's investment has been a relatively small proportion of the overall wheat breeding effort directed at developing countries, this investment continues to have a large impact, particularly in spring habit wheats and particularly outside of China. The large impact of CIMMYT may be attributed to many factors, but three technical explanations and one institutional reason stand out. The most widely noted explanation is that CIMMYT (including its predecessor, the Rockefeller Foundation program in Mexico) was the first institution to incorporate dwarfing genes into wheat varieties aimed at the developing world. Less widely known technical factors include an early commitment to improved disease resistance, which was deliberate, and the incorporation of day-length insensitivity into much of the CIMMYT germplasm, which was a byproduct of early shuttle breeding between different latitudes in Mexico. The institutional factor was the widespread collaboration between CIMMYT and NARS wheat breeding programs, and the resulting access to trial performance data across an extremely wide number of locations and wheat growing environments.

In the 1990s, over half the spring bread wheat varieties released in developing countries were based on crosses made by CIMMYT, with further selection done by NARS. Nearly 90 percent of spring bread wheat releases contained some CIMMYT germplasm. If anything, CIMMYT's influence in spring durum wheat in developing countries was even larger, with over three-quarters of the crosses made by CIMMYT and nearly all the releases containing some CIMMYT germplasm. In contrast, only 15 percent of the winter bread wheat crosses were made by CIMMYT, and only 40 percent of the releases contained some CIMMYT germplasm. Furthermore, unlike spring habit wheats, in earlier periods very little CIMMYT germplasm was present in winter wheats released in developing countries (Heisey, Lantican, and Dubin 2002). This is because wheat breeding in China, the major winter wheat producer among the developing countries, developed rather independently of the international system, and CIMMYT only began to target the winter wheat areas in the Middle East in 1985.

Diffusion of Semidwarf Wheat in Developing Countries

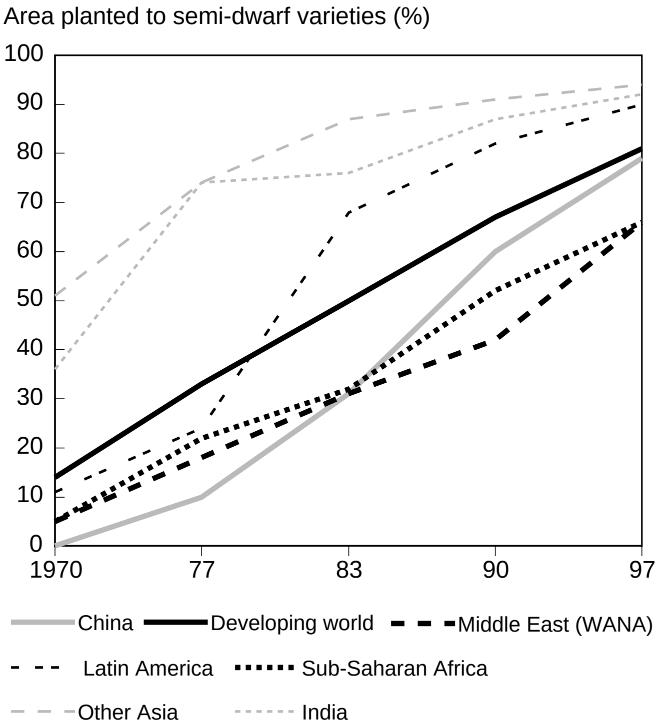
In the developing world, semidwarf Green Revolution varieties diffused fastest and most quickly in South Asia, after their initial use in irrigated wheat production in northwest Mexico.[9] Diffusion in Latin America has also been particularly widespread, and in more recent years shorter stature wheats have covered increasing percentages of wheat area in China. Even in the Middle East and Sub-Saharan Africa, the areas in which diffusion of semidwarf wheats has been slowest, adoption in the late 1990s stood at about two-thirds of total wheat area. In the aggregate, semidwarf wheat varieties are now planted on about 80 percent of the total wheat area in developing countries (fig. C-1). Across the developing world, adoption of modern spring bread wheat varieties, the most commonly grown wheat type, stood at just under 90 percent of spring bread wheat area. Adoption of spring durum wheat high-yielding varieties (HYV) and winter bread wheat HYV was just over 70 percent of the area planted to each of these wheat types.

One of the early criticisms of the Green Revolution was that HYV wheat was thought to require optimum growing conditions in terms of moisture and fertilizer use. In reality, in many instances HYV wheat varieties have performed well in less favorable environments too, compared with earlier varieties grown in these areas, or they have been actively adapted to these less favorable areas. Although adoption of semidwarfs was fastest and highest in more optimum moisture environments, the technology has spilled out into less favorable environments as well. By the late 1990s, adoption of HYV wheat ranged from 80 percent to 100 percent in nearly all irrigated or high rainfall environments for both spring and winter wheat, and between 50 percent and 60 percent in dry spring wheat environments.

[9] Both before and after the Green Revolution, scientific wheat breeding programs in both developed and developing countries continued to release improved tall varieties as well as semidwarfs. Taller improved varieties continue to be widely grown in major wheat-producing regions such as Canada and parts of the United States. Although a few improved tall varieties are still released and grown in a few developing countries, in this latter group of countries the terms "HYV" (high-yielding varieties), "semidwarf" (referring to shorter stature conferred by genes for reduced height) and "improved" (referring to scientifically-bred varieties) have become almost synonymous.

Figure C-1

Percentage wheat area planted to semi-dwarfs in developing countries



Source: Dalrymple 1986; Byerlee and Moya 1993; Heisey, Lantican and Dubin 2002.

HYV wheat was least widely grown (around 30-40 percent) in dry winter wheat environments, in part because these dry winter wheat environments were among the last targeted by the international system (Heisey, Lantican, and Dubin 2001).[10] Lantican, Pingali, and Rajaram (2001) found that in dry and hot spring wheat environments in developing countries about three-quarters of the *improved* wheat area (i.e. area excluding landraces and unknown varieties) was planted to varieties that had one or both parents originating in irrigated environments. This demonstrates that spillover effects from favorable environments have played a major role in the use of HYV wheat in less favorable environments.

In much of the developing world, nearly all the HYV spring wheat varieties released and planted contain considerable genetic material from CIMMYT and the international wheat breeding system. Today, CIMMYT also plays a major role in winter varieties released in the Middle East and Latin America. China is the major exception in the use of CIMMYT-related varieties. Although some CIMMYT germplasm has found its way to China and has been used there, Chinese wheat breeders developed shorter stature wheats more or less independently from the international system. Since the major genes conferring shorter stature appear to have originated in East Asia (Korea or Japan), Chinese breeders independently may have been using the same sources of short stature that also found their way into international wheat breeding from Japan through the United States or Italy (Dalrymple 1986).

India, the other very large developing country wheat producer, has an extensive wheat breeding program with a long history dating to the early 1900s. Many of the post-Green Revolution varieties released by the major wheat breeding programs in India are now several generations removed from original Green Revolution varieties. Much of the crossing has been done by Indian scientists, who have also incorporated some local genetic material. In the late 1990s, large portions of India's wheat area were planted to varieties based on several generations of crosses by these scientists. However, India still makes use of the international system; over the last 5 years the wheat variety that has diffused most rapidly in India is based on a cross made by CIMMYT (Dr. J. Singh, Punjab Agricultural University, personal communication).

One major result of the diffusion of HYV wheat, starting in the early to mid-1960s, has been rapid growth in wheat yields in developing countries. Since the Green Revolution, wheat yields have grown particularly rapidly in China and South Asia. If this yield growth is broken down by periods, however, it is shown that growth has slowed considerably since the mid-1980s (table C-2). The next section looks more closely at this and other phenomena that might provide a few clues about future trends in wheat production in developing countries.

Changes and Challenges in the International Wheat Breeding System

Despite the increases in wheat yields and wheat production in developing countries driven by technological change, production has not kept pace with increases in wheat consumption. Wheat imports have increased rather steadily in most regions of the developing world since the advent of the Green Revolution, with a few notable exceptions (table C-1, sixth column). The exceptions are, as indicated earlier, China, India, and Argentina. China's wheat imports increased

[10] In contrast, scientific plant breeding has developed varieties for the dry, hard red winter wheat environment in the United States over a much longer period of time.

Table C-2--Wheat yield growth in developing countries, 1966-2000

Country/region	Wheat yield growth, 1966-77	Wheat yield growth, 1977-85	Wheat yield growth, 1985-2000	Wheat yield growth, 1966-2000
		Percent/year		
China	4.39	8.36	2.16	4.27
India	4.00	3.85	2.37	3.11
Other Asia (not including West Asia)	4.79	1.87	2.06	2.45
Middle East (West Asia/ North Africa)	2.34	1.67	1.75	2.18
Argentina	3.27	2.69	2.88	2.13 1/
Other Latin America/ Caribbean	-1.70	7.93	1.27	2.28
Sub-Saharan Africa	4.34	0.54	2.26	2.64

1/ Lower total figure for entire period in Argentina is consistent with higher estimates for shorter periods because of the endpoints used.

Source: Calculated from ERS production data with semilog regressions.

in the late 1970s, but fell to relatively modest levels in the late 1990s. Over the past 25 years, India's wheat imports have generally declined. Since the mid-1980s, India has been nearly self-sufficient in wheat. Argentina has always been a wheat exporter, and the trend in its net exports over the past 35 years has generally been upward.

Predicted future wheat consumption and imports by developing countries depend crucially on two sets of assumptions—those that concern production and those that concern consumption. For the most part ERS International Agricultural Baseline Projections (ERS 2002), with a 10-year horizon, make similar predictions to the longer term (to 2020) projections of the International Food Policy Research Institute (IFPRI) (Rosegrant *et al.* 2001). These would include increasing wheat imports by most developing countries, and increasing exports by Argentina. However, these projections differ sharply in the aggregate, largely because of differences in assumptions for China and India. ERS predicts per capita wheat consumption in these countries to remain basically flat from the present onwards, while IFPRI projects modest increases in per capita wheat consumption will continue for most of the next 20 years as income growth and urbanization promote shifts from rice to wheat. ERS projects supply shifts basically on an analysis of trends, while IFPRI explicitly models the effects of investments both in agricultural research as well as in irrigation, rural roads, and education. Both forecasts suggest modest increases in net wheat imports in China, which may be the biggest single uncertain factor in the future of world wheat trade (ERS 2002). ERS expects India to remain a small net exporter, while IFPRI predicts a modest increase in Indian wheat imports over the longer term.

Over the past 10 or 15 years, the rate of growth of wheat yields in developing countries has already decelerated notably. Nonetheless, there is little hard evidence that breeders are making slower progress in increasing wheat yield potential than they have over the entire post-Green Revolution period. Furthermore, breeders have been making gains not only in wheat yield potential, but also in more robust disease resistance. In fact, in favored environments, better disease resistance may be the largest component of current increases in average experimental yields (Sayre *et al.* 1998). There is also evidence that although yield growth has slowed in favored wheat production environments, it has grown faster over certain limited periods in some marginal environments, relative to previous yield increases in these marginal environments. These increases in marginal areas, for example in drier regions of Argentina, or some parts of the Middle East such as Syria and Tunisia, are in large part the result of increased HYV adoption and HYV yield growth. Both the increased adoption and yield growth in marginal environments have resulted primarily from spillovers from research in more favored areas. The evidence for these contentions comes from some analysis of experimental trials, some circumstantial aggregate evidence from farmers' fields, and a few micro-level studies in favorable wheat-growing areas that have been characterized by early HYV adoption and relatively high yields (Byerlee and Moya 1993; Heisey, Lantican, and

Dubin 2002). Because of the difficulties in obtaining aggregate yields based on environments rather than political units, these arguments are not completely conclusive, but they do bear some weight and deserve further scrutiny.

The evidence to date also suggests that the broad international public sector strategy of directing more breeding research efforts on more favored wheat-growing environments, at the same time that some resources are devoted to maximizing spillovers into less-favored environments, has been a successful one. Furthermore, payoffs to investments in disease resistance, for example non-race-specific resistance to leaf rust, are likely to continue to be high. What is less clear is what combination of tactics will be most successful in continuing to advance yield potential in wheat—conventional breeding, hybrid wheat, wide crossing,[11] biotechnology (including functional genomics), and the like. It will also be useful to analyze further the apparent slowdown in wheat yield gains in highly productive environments. This analysis would help to determine possible environmental factors in this slowdown, and to consider what combination of wheat breeding, wheat crop management, and policy will continue to best advance wheat yields, wheat production, and most importantly wheat productivity worldwide. Furthermore, relative prices and changes in consumer tastes and preferences will play an increasing role in determining wheat breeding priorities.

Several major sets of factors related to wheat breeding will be crucial to achieving continued growth in wheat yields and production in developing countries in the future. The first set of factors are development investments, including investment in wheat breeding research, which will be discussed here, as well as complementary investments, which will not be considered in detail. The second set of factors concerns potential environmental constraints to further increases in wheat yields. The third set of factors are institutional, particularly those that affect seed production and distribution, intellectual property, and the flow of germplasm within the international system.

Over the 1990s, there have been notable changes in funding for international wheat improvement research. These changes have been exemplified by a decline in real resources committed to wheat improvement research at CIMMYT since the late 1980s (Heisey, Lantican, and Dubin 2002). CIMMYT wheat improvement research constitutes a relatively small part of the international breeding effort in expenditure terms, but as shown above, its influence is large.

The view has often been expressed that overall real resources devoted to wheat breeding research for developing countries have also declined. At the level of the NARS, there is relatively little hard evidence to support this view. Declines in NARS public-sector investments in wheat breeding research may be easiest to document in Sub-Saharan Africa and possibly parts of Latin America, with anecdotal evidence from other developing countries. It is possible that increases in wheat breeding investment in large producers such as China may have masked declines in investment in smaller producers, but this remains conjecture rather than demonstrable fact. For many countries, even those in which real resources allocated to wheat research have not declined, several additional features may be important. A very high proportion of wheat research investment (80 percent, 90 percent, or higher) in national wheat breeding programs has often gone to salaries, with limited funds remaining for operational budgets crucial to conducting research.[12] Furthermore, it might be possible to increase breeding efficiency with greater reliance on the international system or reallocation of resources within larger countries. In general, many wheat breeding programs targeting relatively small areas within developing countries maintain their own crossing programs, when it would be more cost effective for them either only to test varieties from other programs, or perhaps shut down completely (Maredia and Byerlee 1999).

It is too soon to say how the decline in real breeding resources at CIMMYT will affect the international wheat breeding system. Up through the late 1990s, the pivotal role of CIMMYT in many developing country wheat releases was maintained with some actual increases in the frequency of CIMMYT-related winter releases, a wheat type for which CIMMYT research efforts only really began in the mid-1980s. Since lag times in agricultural research tend to be long, however, it is possible that this decline in real CIMMYT funding may have an adverse effect on the number of wheat varieties that NARS will release from the present onwards.

[11] Wide crossing refers to the incorporation of genetic material from wheat's wild relatives into the wheat breeding germplasm pool.

[12] Anecdotal evidence suggests that large private sector breeding firms in the U.S. may spend about 70 percent of their research budgets on salaries.

What will determine the likely investment in wheat improvement research in China and India, the two largest sources of uncertainty in the level of wheat production in the developing world over the next 20 years or more? On the one hand, these countries stand counter to the trends of stagnant or declining investments in public sector agricultural research, and so simple trend projections would suggest some increases in wheat breeding expenditures. On the other hand, other observers might conclude that having stemmed the tide of rising imports notable in most other developing countries, China and India might not find wheat breeding investment as crucial. One trend is already observable in China, where shifting consumer tastes and preferences have resulted in the development of several different kinds of higher quality wheat varieties. Quality wheat area was estimated to be as high as 3.9 million hectares in 2001/02, but price policies and state grain procurement have not completely adjusted to support incentives for high quality wheat production (Hsu *et al*. 2001). Possibly 30 percent of Chinese wheat breeding resources are currently directed at producing high quality varieties, and this may increase. Management conditions as well as the varieties planted, however, will also influence the quality of harvested wheat (Dr. He Zhong-Hu, CIMMYT regional wheat coordinator, East Asia, personal communication).

Some perspective might come from U.S. experience. Although there have been wide fluctuations in the real price of wheat, the long-run trend for this price has been downwards at least since the end of the Civil War. Technological change has been almost surely a major factor in this trend—first changes in mechanical technology, and, from about 1940, changes in biological technology (new varieties, increasing fertilizer use) that have resulted in a long-run increase in U.S. wheat yields. Long-run levels of investment in wheat research seem to bear little predictable relationship to the long-run declining real price of wheat.

There are a number of reasons why developing countries, including China and India, might continue to invest in wheat improvement research. First, a considerable proportion of current research expenditures in both high-income and developing countries is now devoted to research simply aimed at maintaining yields in the face of evolving pests and diseases (Adusei and Norton 1990; Collins 1995). Second, policymakers and research scientists are concerned about a notable productivity slowdown in the most favorable and most intensively cropped wheat production regions, and the possible environmental factors contributing to this slowdown (Ali and Byerlee 2001). Since it often takes 15 to 20 years from the time a cross is made until the resulting variety reaches its peak area in developing countries (Heisey, Lantican, and Dubin 2002), committing wheat breeding resources now is partially akin to taking out an insurance policy on a highly uncertain future. Demand for wheat will continue to rise in these countries, even if only through population growth, and policymakers usually show marked preferences for meeting a sizeable proportion of domestic demand for such an important commodity through domestic production. Third, once a country's farmers start using the results of scientifically based agricultural research, they are, in a sense, on a "technological treadmill." The relatively modest amounts necessary to fund cost-reducing wheat improvement research can be complementary, not competitive, with more market-oriented price policies at a national level.

Potential effects of environmental factors are also illustrated by the two crucial large wheat producers, China and India, as well as other countries in Asia. Some observers feel that wheat breeding investments alone may not be sufficient to overcome land degradation or competition with nonagricultural sectors for crucial resources such as water (Rosegrant *et al.* 2001). Ali and Byerlee (2001) provide a fairly comprehensive study, in this case for Pakistan, of the effects of declining land quality on agricultural production in wheat based systems, and suggest that greater attention will need to be given to crop and water management in addition to varietal development in research for these systems.

One institutional issue affecting future impacts of wheat breeding research has been evident for some time. In areas where HYV wheat was adopted relatively early, older varieties are continuously replaced by newer ones. However, lengthy adoption lags often continue to reduce research impacts below what they would be were new varieties to reach farmers faster. These adoption lags are related to the performance of wheat seed systems, and to the performance of institutions such as agricultural extension.

More recently, increased intellectual property rights (IPR) protection for plants has influenced plant breeding in both developed and developing countries. There is fairly widespread acceptance that some level of IPR protection for plant varieties is desirable, but there is considerable disagreement over how strong this protection should be in the future. For example, should research and farmer exemptions to plant IPR be limited, as they have been increasingly in many high income nations? In theory, IPR encourage innovation (in this case the development of new wheat varieties) at some cost in temporary monopoly granted to the innovator (in this case the wheat breeding institution). But some observers have also noted a second potential cost of increased IPR for products in which innovation is cumulative, which is certainly the case in wheat breeding. If initial IPR for plant varieties are too strong, progress in plant breeding may be slowed if other researchers are not allowed to use these varieties in their breeding programs.

IPR are almost certain to be a crucial factor in the use of biotechnology innovations in wheat, where they have not yet reached commercial varieties. But they are also already influencing so-called conventional wheat breeding as well. Formal materials transfer agreements are becoming commonplace, and there are continuing controversies over issues such as private firms securing IPR for varieties that have been developed from germplasm obtained freely from the international system. Because of the long history of widespread exchange of genetic material among different wheat breeding programs in both developed and developing countries, wheat breeders are sometimes at the forefront of those warning of potentially deleterious effects of increasing IPR protection (Kronstad 1996). Empirical evidence of the effects of IPR protection on innovation in general is mixed, varying widely by industry, (Jaffe 2000), and this is certainly the case for plant breeding. In the United States, for example, Knudson and Hansen (1991) found that private wheat seed producers often were unable to charge a price high enough to cover the costs of their breeding programs at the same time that the price was low enough to make the use of private wheat seed attractive to farmers. Furthermore, Alston and Venner (2000) concluded that the U.S. Plant Varietal Protection Act (PVPA) contributed to increased investment by State agricultural experiment stations in developing new wheat varieties, but that private sector efforts in developing non-hybrid wheat varieties had not increased. In addition, the PVPA did not appear to have contributed to greater technical progress in wheat breeding.

As a result, it is not possible to make strong *a priori* arguments about the likely net impacts of increasing IPR on wheat breeding. Given the importance of widespread germplasm exchange in the international system, however, and the relative unimportance of private wheat breeding for much of the developing world, it seems quite unlikely that in the near future stronger IPR would call forth sufficiently increased private sector wheat breeding investment to replace public sector breeding to any significant degree.

Conclusion

The international wheat breeding system that developed with and after the Green Revolution has had several major impacts. First, adoption of modern wheat varieties continued in the post-Green Revolution period, with new modern varieties replacing older ones in areas of early adoption, and the spread of modern varieties into other wheat growing areas as well. Second, particularly outside of China, the international wheat breeding system as exemplified by CIMMYT and its NARS partners has continued to be an important source of genetic material for post-Green Revolution wheat varieties. Third, diffusion of modern wheat varieties has been a major factor in the rapid growth of wheat yields in many developing countries, and the internal rate of return to investment in international wheat breeding research has been high, estimated at 52 percent for the period 1977-90 (Byerlee and Moya, 1993; Byerlee and Traxler 1995).

However, the future performance of the system remains in question. Already wheat yield increases have slowed in many developing regions, in part because steady increases in post-Green Revolution yields are nonetheless not as spectacular as one-time yield increases resulting from the initial adoption of high-yielding wheat varieties. Other potential explanations for slowing yield growth include declining returns to wheat production and environmental constraints to further intensification of wheat production. Although investments in wheat breeding have apparently remained strong in the very largest developing-country wheat producers, in other NARS and at CIMMYT, real resources devoted to wheat breeding have declined over the past 10 to 15 years. Finally, institutional changes, particularly the strengthening of intellectual property protection for plant varieties, will have large but uncertain effects on the impacts of international wheat breeding research.

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