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WORLD WHEAT FACTS AND TRENDS

Global Wheat Research in a Changing World: Challenges and Achievements

P.L. Pingali, Editor

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INTERNATIONAL MAIZE AND
WHEAT IMPROVEMENT CENTER

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Abstract: This report has four parts. The first part focuses on the changing environment in which the international wheat research system functions in developing countries. The authors describe recent trends in developing country wheat production against projected demand for wheat. Next, they present strategies for increasing productivity in favored and less favored wheat production environments. Part 1 concludes with a discussion of how emerging trends and policies, such as intellectual property protection and market liberalization, are likely to affect the global wheat research system and exchange of germplasm. Part 2 of the report presents new information on the historical impact of the international wheat improvement system, including information on the role of CIMMYT germplasm. Part 3 discusses wheat supply and demand projections, with a special focus on Asia (including Central Asia). Part 4 presents statistics on world wheat production and consumption in a newly revised format.

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Contents

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Foreword

Previous reports in our *Facts and Trends* series have examined the accomplishments of the global wheat improvement research system and also have forecast needs for wheat technology in specific environments throughout the world. In this report, for the first time, we examine the global wheat improvement effort from both of these complementary perspectives. As the title of our report indicates, we offer a comprehensive overview of past achievements and future strategies for wheat breeding in developing countries.

The new millenium is ushering in challenges as well as opportunities for research programs. The Green Revolution and the emerging international wheat improvement system matured in conditions that were extremely conducive to agricultural research and development, but these conditions have evolved into a new set of circumstances: the globalization of the world economy, including the world wheat economy; the trend towards increasing protection of intellectual property; the weakening of many public-sector research programs in developing countries; reduced recognition of agriculture as a stimulus for economic development; and the tendency to restrict the flow of experimental germplasm throughout the world.

As these changes in the wheat research environment become more widespread, the developing world's demand for wheat will not remain static. Demand is continuing to grow. According to recent projections by the International Food Policy Research Institute, wheat imports in developing countries will more than double between 1993 and 2020. A major challenge for the research and development community will be to devise strategies for meeting this rising demand in a more volatile research setting. Part 1 of our report reviews projected increases in wheat demand in developing countries and describes the options for raising wheat productivity in favorable and less favorable wheat production environments. What is proposed in Part 1 is nothing less than an international wheat improvement agenda for the next five to ten years. Success will depend as much on advances in science as on a less predictable factor: the support that will enable researchers to achieve their goals.

As Part 2 of this report demonstrates, over the past three decades the international research system has proven to be uniquely suited to meeting the needs of poor farmers and consumers in developing countries. Data from our most recent study of the impacts of global wheat research confirm that the longstanding collaboration between CIMMYT and national wheat breeding programs in developing countries has yielded impacts on a scale that many research efforts rarely achieve. For example:

- The percentage of spring bread wheat releases that were CIMMYT crosses or had at least one CIMMYT parent was even higher in 1991-97 (84% of spring wheats released in the developing world) than in earlier periods.
- Sixty-two percent of the developing world's wheat area is sown to wheats with CIMMYT ancestry.
- Eighty to ninety percent of the developing world's spring bread wheat area outside of China is planted to CIMMYT-related wheats. In China alone—the world's largest wheat producer—36% of the spring bread wheat area is sown to CIMMYT-related wheats.

Arguably this global impact is unmatched in its extent by any other development initiative. Simply put, wheat is the most widely consumed food grain in the world, and CIMMYT germplasm underpins the crop in the South and also contributes significantly to wheat production in the industrialized world (for example, in Europe, the USA, and Australia). CIMMYT has made a true contribution to global food security. Based on these achievements, the global wheat improvement system merits major support for its research agenda in the years to come.

A main purpose of CIMMYT's *Facts and Trends* series is to explore the difficult issues related to maize and wheat research in developing countries. This report explores many such issues—including serious questions about safeguarding the flexibility of the global wheat improvement system—but here I would like to raise two more. Although they remain largely unspoken in the pages that follow, these questions lie at the heart of this report, and I would ask readers to consider them as they proceed. First, if the global wheat research system had not existed, what kind of world would we have inherited? Second, if that system should cease to operate efficiently, what legacy will we leave future generations? Of all of the issues proposed for consideration in this report, these two may be among the most relevant for directing future research and development strategies.

Timothy Reeves

Timothy G. Reeves
Director General

Part 1

Global Wheat Research in a Changing World: Options for Sustaining Growth in Wheat Productivity

Prabhu L. Pingali and Sanjaya Rajaram

By 2020, demand for wheat is expected to be 40% greater than its current level of 552 million tons (Rosegrant et al. 1997), but the resources available for wheat production are likely to be significantly lower. Viewed in this light, the challenge for increasing wheat supplies in the developing world is as great today as it was three decades ago at the start of the Green Revolution.

The strategies that developing countries adopt to meet future demand for wheat will depend a great deal on how they are affected by the changes that are sweeping the world economy and transforming the way we conduct research. As global food markets become increasingly integrated, the premium once placed on food self-sufficiency is being superseded by an emphasis on economic competitiveness and comparative advantage. Agricultural resources are increasingly diverted from cereal crop production to other agricultural and nonagricultural activities. Research systems, national as well as international, face declining budgets and uncertain futures. The free international movement of germplasm and information, which was an important force behind the Green Revolution, is increasingly circumscribed by plant quarantine restrictions and intellectual property protection.

What strategy should the global wheat research system pursue in this changing world? The answer explored here is for the research system to focus on sustaining the competitiveness of wheat production in developing countries. This goal can be achieved through a shift in the yield frontier, a constant drive to stabilize yields, and enhanced input use efficiency and input responsiveness in wheat varieties. The emphasis on improving the profitability of wheat production should not be restricted to irrigated, favorable environments; similar opportunities ought to be explored for marginal, rainfed environments.

In exploring these issues, we focus on the roles that global wheat research and germplasm exchange have played—and should play—in sustaining growth in wheat productivity over the next two decades. After discussing past trends in wheat productivity, we review potential technological advances for favorable and marginal wheat environments. We conclude by discussing how the integration of world food markets, economic liberalization, and greater intellectual property protection are likely to affect the chief source of gains in wheat productivity: the global system of germplasm and information exchange.

Why Worry about Wheat Productivity?

The development and release of modern wheat varieties in the early 1960s triggered the Green Revolution. The first and most important factor contributing to the success of the wheat revolution was wheat itself: semidwarf, high-yielding, rust-resistant wheat seed. The second was the establishment of a free, unrestricted global wheat research system based on the exchange of germplasm. The third was large-scale investment in fertilizers, irrigation, and transportation infrastructure. Lastly, the strong political will in developing nations to achieve food self-sufficiency, combined with a conducive agricultural policy environment, also contributed to success.

The largest gains in productivity were made in land-scarce countries, where the new seed and fertilizer technologies fostered rapid growth in land productivity. By the late 1970s, 40% of the wheat area in developing countries was sown to modern high-yielding varieties; the figure for Asia was close to 70% (Table 1). By 1994, 78% of developing country wheat area was under modern varieties. The corresponding figure for Asia was 91% and, for Latin America, 92%.

Between 1961 and 1994, wheat yields increased at an average annual rate of more than 2% in all developing countries except China and India, the two largest wheat producers (Pingali and Heisey 1996). Wheat yields in China and India grew extremely rapidly over much of this period. Yields in India rose sharply in the early years of the Green

Revolution, from the mid-1960s until the late 1970s. Although rates of growth in wheat yields in these countries have declined since the late 1980s, they have still been 2% per year or more in the latest periods for which data are available. Wheat yields in South and East Asian countries other than China and India grew at an average rate of 2.75% annually over 1961-94, displaying much the same pattern as seen in India but slowing more markedly in recent years.

The West Asian/North African countries and the wheat-producing countries of sub-Saharan Africa also experienced rapid wheat yield growth from 1961 to 1994, approximately 2.4% per annum. Latin America lagged behind with a yield growth rate of around 1.8% per annum, although it started from a higher base. In West Asia/North Africa, Latin America, and sub-Saharan Africa, rates of yield increase have tended to vary over time, but, except for the last region, they have been lower in later periods than during the first two decades of the Green Revolution. (The potential implications of slower rates of yield growth are discussed in the next sections of this report.)

From the mid-1970s onwards, wheat production has grown at a faster pace than population. A similar trend has occurred for rice. The increased yields of these two major cereal crops belied the widespread fear that the world would run out of food. Instead, the world has gained access to more and cheaper food. Since the mid-1970s, global wheat prices have declined in real terms, resulting in significant consumption benefits for both the urban and rural poor (Figure 1).

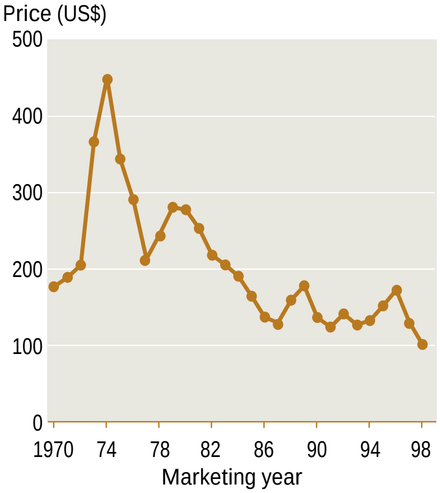

Figure 1. Wheat price (1990 constant US$).
Source: Prices, ERS-USDA; deflator, International Monetary Fund.

The international investment in breeding more productive wheats for developing countries paid off handsomely. The rates of return to wheat research have generally been calculated at 50% or more for individual developing countries since the early 1970s (Table 2).

Given all of these achievements, why should anyone be concerned about wheat productivity? The wheat revolution was good for the majority of poor people, but the world has changed in the three decades since farmers sowed the first seeds of the Green Revolution. The forces that drive productivity gains in wheat are changing. They can be expected to transform how and where wheat is produced, and for what purposes; they will also change the objectives of wheat research, the way it is conducted, and the way its products are made available to farmers. They may well determine whether poor farmers and consumers have enough food to eat in 2020.

Table 1. Percentage area planted to modern varieties of wheat[a] in developing countries, 1970–97

	1970	1977	1983	1990	1994	1997[d]
Sub-Saharan Africa	5	22	32	52	59	56
West Asia/North Africa	5	18	31	42	57[c]	61
South and Southeast Asia	42	69	79	88	91	92
China	na	na	na	70	70	90
Latin America	11	24	68	82	92	88
All developing countries	20[b]	41[b]	59[b]	70	78	82

Source: Byerlee and Moya (1993); CIMMYT (1996); CIMMYT wheat impacts database.

a Excludes tall varieties released since 1965. If these varieties are included, the area under modern varieties increases.

b Excludes China.

c Important countries such as Morocco and Iran not included.

d Excludes unknown cultivars (i.e., those for which pedigree and origin are not known).

Table 2. Studies of returns to investment in wheat research

Study	Year	Country	Period	Rate of return (%)
Ardito–Barletta	1971	Mexico	1943–63	90
Eddleman	1977	USA	1978–85	46
Kislev and Hoffman	1978	Israel	1954–73	125–150
Pray	1980	Bangladesh	1961–77	30–35
Sundquist et al.	1981	USA	1977	97
Otto and Havlicek	1981	USA	1967–79	81
Yrarrazaval et al.	1982	Chile	1949–77	21–28
Zentner	1982	Canada	1946–79	30–39
Nagy	1983	Pakistan	1967–81	58
Ambrosi and Cruz	1984	Brazil	1974–90	59–74
Furtan and Ulrich	1985	Canada	1950–83	29
Norton et al.	1987	Peru	1981–2000	18–36
Evenson and da Cruz	1989	Brazil	1979–88	110
Byerlee	1990	Pakistan	1978–87	16–27
Evenson and McKinsey	1991	India	1972–84	51
Morris et al.	1992	Nepal	1960–90	75–84
Macagno and Gómez Chao	1993	Argentina	1967–92	42

Source: Echeverría, cited by Morris et al. (1994); CIMMYT (1993).

The next two sections of this report describe some of the forces influencing gains in wheat productivity and how they have changed over the years. To understand these changes and their implications for future gains in wheat productivity, we review the progress of the Green Revolution in favorable (irrigated) and marginal (dryland) environments, and then we examine how growth in yield, trends in input use, and types of production incentives have changed since the wheat revolution began. For an overview of the various wheat production environments, see the box, "Wheat Mega-Environments Defined," p. 4.

The Changing Nature of Wheat Productivity: The Early Green Revolution Years

The first gains in wheat productivity were seen in irrigated and high-rainfall environments, the so-called favorable production environments. By 1977, 83% of the wheat area in these environments was planted to modern, high-yielding wheats. By 1990, this figure was close to 100% (Byerlee and Moya 1993).

The irrigated wheat-growing environments exhibited substantial yield growth. In northwestern Mexico, for instance, average farm yields had risen from 2.2 t/ha in 1960 to 6.0 t/ha in 1998, almost a three-fold increase (CIMMYT Economics Program data). Similarly, in the Indian Punjab, average yields rose from 1.5 t/ha in 1960 to 3.5 t/ha in 1989 and 4.2 t/ha in 1999 (Sidhu and Byerlee 1992; Punjab Agricultural University, pers. comm.).

During the first three decades after modern varieties were introduced, the yield potential of subsequent generations of modern varieties in favorable environments rose by 1% per annum (Byerlee and Traxler 1995) (Table 3). The initial yield boost of 35-40% on farmers' fields was followed by a period of less dramatic but nonetheless steady yield growth, during which the second- and third-generation varieties with higher yield potential and increased disease resistance replaced the original improved varieties (Byerlee and Morris 1993).

The rainfed environments, marginal for wheat production, also benefited from technological change. First they benefited from a spillover of new varieties from the irrigated environments; later, from new varieties adapted to rainfed conditions, especially varieties with improved drought tolerance. By 1990 approximately 44% of all wheat varieties released were bred specifically for dryland environments (Table 4).

Table 3. Experimental evidence on rates of genetic gain in yields in spring wheat resulting from the release of new varieties (yield maintenance effect not included)

Environment/location	Period	Rate of gain (%/yr)	Data source
Irrigated			
Sonora, Mexico	1962–75[a]	1.1	Fischer and Wall (1976)
	1962–83[a]	1.1	Waddington et al. (1986)
	1962–81[a]	0.9	P. Wall, CIMMYT[b]
	1962–85[a]	0.6	Ortiz–Monasterio et al. (1990)
	1962–89[a]	0.7	K.Sayre, CIMMYT[b]
Nepal	1978–88[a]	1.3	Morris, Dubin, and Pokhrel (1994)
Northwest India	1966–90[a]	1.0	Jain and Byerlee (1994)
Pakistan	1965–82[a]	0.8	Byerlee (1993)
Sudan	1967–87	0.9	Byerlee and Moya (1993)
Zimbabwe	1967–85[a]	1.0	Mashiringwani (1989)
Rainfed			
Paraguay	1972–90	1.3	M.Kohli, CIMMYT[b]
Victoria, Australia	1850–1940	0.3	O'Brien (1982)
	1940–81	0.8	
New South Wales, Australia	1956–84	0.9	Antony and Brennan (1988)
Western Australia (low rainfall)	1884–1982	0.4	Perry and D'Antuono (1989)
Central India	1965–90	0.0	Jain and Byerlee (1994)
Acid soils (rainfed)			
Rio Grande do Sul, Brazil	1976–89	3.2	Byerlee and Moya (1993)
Paraná, Brazil	1969–89	2.2	Byerlee and Moya (1993)

Source: Byerlee and Traxler (1995).
Note: Regression results and data available from authors.
[a] Semidwarf varieties only.
[b] Unpublished data.

Table 4. Distribution of wheat varieties released in developing countries, by wheat type and ecological niche, 1966–97

	Percent recommended for:					
	Well-watered/irrigated		Dryland		Both	
Wheat type/region	1966–90	1991–97	1966–90	1991–97	1966–90	1991–97
Spring bread wheat	37	58	45	18	19	24
Sub-Saharan Africa	36	72	39	8	25	20
West Asia/North Africa	57	51	14	42	29	7
South and East Asia	70	58	14	9	16	33
Latin America	13	56	71	15	15	29
Winter bread wheat	26	46	56	32	18	22
Spring durum wheat	43	41	34	30	20	29
All	37	53	44	23	19	24

Source: Byerlee and Moya (1993); CIMMYT wheat impacts database.

Wheat Mega-Environments Defined

In the mid-1980s, CIMMYT refined its definitions of the environments to which it targets its wheat germplasm by grouping them into “mega-environments” (MEs), which were developed based on a mixture of plant, disease, soil, climatic, and socioeconomic characteristics. An ME is a broad, frequently transcontinental but not necessarily contiguous area occurring in more than one country. It is defined by similar biotic and abiotic stresses, cropping systems requirements, consumer preferences, and, for convenience, volume of production. The MEs are useful for defining breeding objectives because each one encompasses millions of hectares sharing a certain degree of homogeneity for wheat production (Dubin and Rajaram 1996).

Characteristics of wheat mega-environments (ME)

Wheat type and ME	Latitude (degrees)	Moisture regime[a]	Temperature regime[b]	Sown	Breeding objectives[c,d]	Representative locations or regime	Year breeding began at CIMMYT
Spring wheat							
ME1[d]	<40	Low rainfall, irrigated	Temperate	Autumn	Resistance to lodging, SR, and LR	Yaqui Valley, Mexico; Indus Valley, Pakistan; Gangetic Valley, India; Nile Valley, Egypt	1945
ME2	<40	High rainfall	Temperate	Autumn	As ME1 + resistance to YR, *Septoria* spp., *Fusarium* spp., and sprouting	Mediterranean Basin; Southern Cone; Andean Highlands; East African Highlands	1972
ME3	<40	High rainfall	Temperate	Autumn	As ME2 + acid soil tolerance	Brazil, Andean Highlands; Central Africa; Himalayas;	1974
ME4A	<40	Low rainfall, winter rain	Temperate	Autumn	Resistance to drought, *Septoria* spp., and YR	Aleppo, Syria; Settat, Morocco	1974
ME4B	<40	Low rainfall, winter drought	Temperate	Autumn	Resistance to drought, *Septoria* spp., *Fusarium* spp., LR, and SR	Marcos Juárez, Argentina	1974
ME4C	<40	Mostly residual moisture	Hot	Autumn	Resistance to drought	Indore, India	1974
ME5A	<40	High rainfall/ irrigated, humid	Hot	Autumn	Resistance to heat, *Helminthosparium* spp., *Fusarium* spp., and sprouting	Joydebpur, Bangladesh; Encarnacion, Paraguay	1981
ME5B	<40	Irrigated, low humidity	Hot	Autumn	Resistance to heat and SR	Gezira, Sudan; Kano, Nigeria	1975
ME6	>40	Moderate rainfall, summer dominant	Temperate	Spring	Resistance to YR, LR, *Fusarium* spp., *Helminthosporium* spp., sprouting	Harbin, China	1989
Facultative wheat							
ME7	>40	Irrigated	Moderate cold	Autumn	Rapid grain fill, resistance to cold, YR, PM, BYD	Zhenzhou, China	1986
ME8A	>40	High rainfall, long season	Moderate cold	Autumn	Resistance to cold, YR, *Septoria* spp.	Temuco, Chile	1986
ME8B	>40	High rainfall, short season	Moderate cold	Autumn	Resistance to *Septoria* spp., YR, PM, *Fusarium* spp., sprouting	Edirne, Turkey	1986
ME9	>40	Low rainfall	Moderate cold	Autumm	Resistance to cold, drought	Diyarbakir, Turkey	1986
Winter wheat							
ME10	>40	Irrigated	Severe cold	Autumn	Resistance to winterkill, YR, LR, PM, BYD	Beijing, China	1986
ME11A	>40	High rainfall, long season	Severe cold	Autumn	Resistance to *Septoria* spp., *Fusarium* spp., YR, LR, PM	Odessa, Ukraine	1986
ME11B	>40	High rainfall, short season	Severe cold	Autumn	Resistance to LR, SR, PM, winterkill, sprouting	Lovrin, Romania	1986
ME12	>40	Low rainfall	Severe cold	Autumn	Resistance to winterkill, drought, YR, bunts	Ankara, Turkey	1986

Source: Rajaram and Van Ginkel (1996).

a Rainfall refers to just before and during the crop cycle. High = > 500 mm, low = < 500 mm.

b Refers to the mean temperature of the coolest month. Hot = >17 C; temperate = 5-17 C; moderate cold = 0-5 C; severe cold = -10-0 C.

c Factors additional to yield and industrial quality. SR = stem rust, LR = leaf rust, YR = yellow (stripe) rust, PM = powdery mildew; BYD = barley yellow dwarf.

d Further subdivided into: (1) optimum growing conditions, (2) presence of Karnal bunt, (3) late planted, and (4) problems of salinity.

By 1992, 12 MEs involving spring wheats (ME1 to ME6), facultative wheats (ME7 to ME9), and winter wheats (ME10 to ME12) had been defined (see table). Spring wheat MEs cover almost 95 million hectares in the developing countries, excluding China, while facultative/winter wheat MEs cover almost 25 million hectares (Dubin and Rajaram 1996). Of the 12 MEs, by far the most important in area and production is the irrigated spring wheat environment, where 40% of the developing world's wheat is produced. Spring wheat—durum wheat and bread wheat together—makes up 75% of total wheat production in developing countries (including China) (CIMMYT wheat impacts database). For this reason, the discussion in this report emphasizes the spring wheat MEs. The characteristics of the six spring wheat MEs used by the CIMMYT Wheat Program are summarized in the table. Of these six MEs, ME1 and ME2 are considered the favorable wheat environments, and ME3 to ME6 are the marginal ones.

Byerlee and Traxler (1995) reported that over the past few decades the yield potential of drought-tolerant varieties has risen at a modest 0.5% per annum (Table 3).

Rainfed area sown to modern wheat varieties has risen steadily since the mid- to late 1970s (see Figure 2 for examples). Yield gains from the adoption of modern varieties in these marginal environments have been modest (Byerlee and Morris 1993), but an observable drop in yield variability has resulted from the release of wheat germplasm possessing improved tolerance to drought and other abiotic stresses. Using time-series data for 57 countries, Singh and Byerlee (1990) found that variability in wheat yields declined by an average of 23% from 1951-65 to 1976-86. Table 5 shows that the coefficient of yield variability dropped by 9% in the dryland temperate environments and by 16% in the tropical environments. Wheat yield variability dropped significantly in the irrigated environments as well.

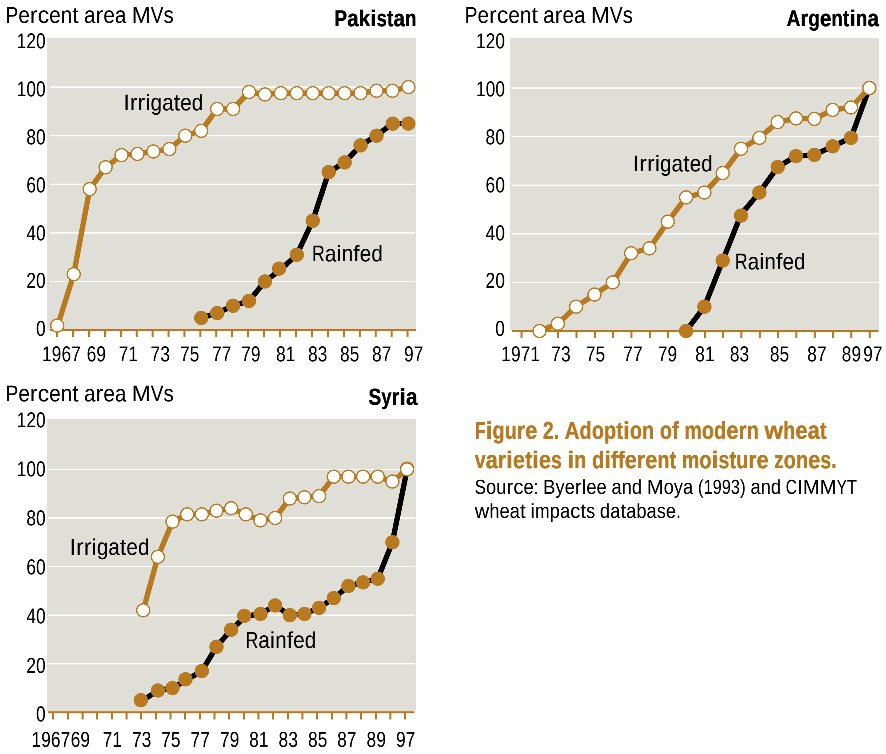

Figure 2. Adoption of modern wheat varieties in different moisture zones.
Source: Byerlee and Moya (1993) and CIMMYT wheat impacts database.

Table 5. Changes in the variability of wheat yields in selected groups of countries, 1951–86

	Number of countries	Coefficient of variation (CV) around trend (%) 1951–65	 1966–75	 1976–86	Percent change in CV, 1951–65 to 1976–86
Irrigated and well-watered temperate	36	10.6	8.5	6.4	–38
Dryland temperate	15	16.2	15.2	14.4	–9
Tropical	6	22.6	23.6	18.9	–16
All countries	57	13.3	11.8	10.1	–23

Source: CIMMYT (1991).

Wheat Productivity, 1985 to the Present: New Concerns

As noted, for the first time since the start of the Green Revolution, serious concerns about future wheat supplies have emerged. Newer generations of high-yielding varieties continue to exhibit higher yield relative to earlier varieties, but the rate of growth in yield potential has slowed considerably in the most recent decade (Sayre 1996).

In environments favorable to wheat production, the economically exploitable gap between potential yields and yields achieved on farmers' fields has been reduced considerably over the past three decades.[1] In other words, in these areas the cost of marginal increments in yield, given existing technologies and policies, could exceed the incremental gain. The cost is high not only in terms of increased use of inputs such as fertilizer, fuel, and water, but also in terms of increased management and supervision time for achieving more efficient input use (Pingali and Heisey 1996; Byerlee 1996).

Productivity growth in the irrigated environments has also been affected by the decline in irrigation investments since the early 1980s. Reduced expenditures on irrigation have not only limited the expansion in irrigated area but have negatively affected the maintenance of infrastructure (Rosegrant and Pingali 1994). Decades of poor water management have caused large tracts of irrigated land to be abandoned or cultivated at low productivity levels because of salinization. The Indian Punjab, Pakistani Punjab, Yaqui Valley in northwestern Mexico, and the irrigated wheat areas in the Nile Valley exhibit visible signs of land degradation from salinity buildup. Salinity is thought to affect nearly 10 million hectares of wheat in developing countries.

In marginal environments, farmers will face increasing difficulty in capturing further productivity gains. Factors related to plant variety and crop management are the basis for this prognosis. The gains farmers receive from using wheat varieties originally developed for irrigated environments (i.e., spillovers or spillins) will decrease. Additional genetic gains will have to come from breeding efforts targeted specifically to the unique characteristics of marginal environments. Furthermore, farmers in less favorable production areas cannot fully exploit the yield potential of the varieties they grow until they have adequate management practices, which presumably would differ from practices used in irrigated environments. Outside of the Anatolian Plateau of Turkey and rainfed wheat areas of Argentina, little effort has been devoted to developing wheat management practices for marginal environments.

Finally, farm-level incentives for increasing productivity growth in either favored or marginal areas are much weaker today than during the first two decades of the Green Revolution. Output price protection and input subsidies, the hallmarks of Green Revolution agricultural policy, have been removed or are being removed in most developing countries. Gradually, a global movement towards free trade and economic integration is replacing the closed-economy, food-self-sufficiency model that made the Green Revolution so successful. The new paradigm for food policy is self-reliance and comparative advantage rather than self-sufficiency. Related changes in the global wheat economy include the liberalization of wheat imports and a long-term decline in real wheat prices, coupled with rising costs of inputs, especially labor, land, and water. Investments in strategies for increasing growth in the productivity of cereal crops, including wheat, will be affected significantly by these changes in paradigm and policy.

Enhancing Wheat Productivity in Favorable Environments

Given the trends we have just described, the competitiveness of wheat farming will depend on opportunities for dramatically reducing unit costs of production. This can be achieved either by shifting the yield frontier and/or increasing input-use efficiency. Research should ensure that the rate of increase in wheat yields surpasses the rate of increase in input use, so the unit cost of production will decline. For wheat farming to remain profitable, technological change ought to ensure that production costs per ton of wheat are falling at least at the same rate as the real price of a ton of wheat.

The following sections describe genetic and crop management technologies that CIMMYT and national research programs are developing to sustain the profitability of wheat production in the irrigated and high-rainfall areas of developing countries. Genetic improvement research is targeted towards shifting the yield frontier, reducing yield variability caused by biotic and abiotic stresses, and

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[1] Sidhu and Byerlee (1992) provide evidence for the Indian Punjab; similar evidence is available for northwestern Mexico (CIMMYT Economics Program data).

increasing input-use efficiency. Crop management research focuses on improving the partial factor productivity (output per unit of input) of land, fertilizer, water, power, and human labor.

Shifting the Yield Frontier

Over decades, breeders have learned that breeding/selection methods and experimental field designs contribute to breeding progress but in themselves are not powerful enough to overcome inferior germplasm. What matters most in plant breeding is germplasm (Rasmusson 1996). Circumstantial evidence from practical breeding experience supports the idea that breakthroughs in yield potential have largely resulted from wider utilization of plant genetic resources (Rajaram and van Ginkel 1996).

Researchers at CIMMYT are investigating two major strategies, distinct but interrelated, for achieving a dramatic shift in the wheat yield frontier: changes in plant architecture and the exploitation of heterosis (i.e., the development of hybrid wheat). Significant progress has been made in both areas, and the prospects for a substantial shift in the yield frontier within the next decade are good.

Changes in wheat plant architecture. Wheat plant architecture has evolved over the past 45 years, primarily to sustain growth in genetic yield potential. Efforts to develop the first semidwarf wheat varieties in Mexico sought to reduce lodging by reducing plant height, thereby enabling plants to respond more effectively to fertilizer. The dwarfing genes possessed by semidwarf wheats also positively affected yield by allowing more tillers to survive and thus increasing biomass. Controlled experiments showed that wheat yields increased by at least 15% in semidwarf wheats compared to yields of tall varieties (Hoogendoorn et al. 1988). Farm-level yields increased substantially more, however, because of the modern varieties' enhanced responsiveness to fertilizer. The new varieties also increased the prospects for intensified land use because they carried genes for photoperiod insensitivity and early maturity (for example, in South Asia the new wheats matured quickly enough for farmers to add them to their rice cropping systems). Modern semidwarf wheats were also fortified genetically with durable stem and leaf rust resistance to ensure high yields.

In the late 1960s, the first set of semidwarf wheats was hybridized with winter wheats, producing high-yielding spring x winter wheat varieties. The most successful of these crosses developed by CIMMYT is Veery. Compared to other modern wheats, Veery lines have a significantly higher grain number and biomass. Although the wheat kernels of Veery wheats are smaller than those of other contemporary varieties, the drop in size is less than proportional to the increase in grain number, hence the significant positive effect on yields. Veery lines yield 10–15% more than the first generation of modern semidwarf varieties. The Veerys and their progenies (including the Kauz, Attila, Pastor, and Baviacora lines) respond not only to good growing conditions but also demonstrate superior performance under a number of abiotic stress conditions, such as drought and heat, and are more efficient at using nitrogen and phosphorus.

The next step in changing plant architecture is to design wheats with thicker stems, fewer tillers, larger heads, and a higher number of grains without a commensurate decline in grain weight. This change should increase yields by improving the harvest index and input use efficiency. Through 20 years of pre-breeding, genetic manipulation, and countless recombinations, CIMMYT breeders have developed a new wheat type called Buitre, which has a robust stem, long head (>30 cm), multiple spikelets, florets with large glumes, a large leaf area, and broad leaves.

Presently these positive traits are counterbalanced by an unknown physiological imbalance or disorder that results in a low number of tillers, largely sterile heads, mostly shriveled grains, and high susceptibility to leaf and stripe rusts (Rajaram, Singh, and van Ginkel 1996). CIMMYT is improving the Buitre ideotype to develop a plant that has a large number of spikes, a slightly reduced head size, and completely restored fertility. Such genetic stocks could potentially increase yields by 10–15% above those of the Veery descendants in subtropical environments (Rajaram, Singh, and van Ginkel 1996). In sub-temperate environments, where the grain filling period is longer, yields may increase by 20–30%. To achieve these yields, better soil fertility management and well-timed irrigation management are needed. The probability of success in generating these varieties is high, and they could be available for farmers to test in 10 years. This new generation of wheat is primarily targeted for irrigated environments where the economically achievable yield increases from present-day cultivars grown under optimal management are small.

Hybrid wheat. A hybrid is the first-generation offspring of a cross between genetically different parents of a plant species. Hybrids exploit a phenomenon called "hybrid vigor" or "heterosis," which is best described as the tendency of offspring to perform better than either of their diverse parents. Breeders have developed hybrid maize and rice, but the advent of hybrid wheat has been slower for several reasons. Jordaan (1996) and Picket (1993) have attributed this lag to the high cost of male sterilization and seed production, hybrids' limited heterotic advantage, and their lack of agronomic, quality, or disease resistance advantages over inbred lines. Hybrids have thus failed to perform better than successive generations of modern cultivars, especially given that yields of those cultivars have risen by 1% per annum over the past three decades (Byerlee and Moya 1993). Results, however, from South Africa (Jordaan 1996) and across locations in the southern Great Plains of the US (Peterson et al. 1997) have shown that the mean grain yield of hybrids was significantly higher than that of pure lines. A 12–17% advantage in hybrid yield over the leading check cultivars has also been reported (Edwards 1995 and Monsanto 1997, cited in Çukadar et al. 1997).

Interest from the national programs of China and India led CIMMYT to re-initiate its hybrid wheat program in 1996. The CIMMYT program aims to develop a practical hybrid seed production scheme and identify hybrids with high yield potential under favorable irrigated conditions. Three other developments have made it worthwhile to reassess hybrids: improvements in chemical hybridization agents (CHA), the emergence of the new Buitre plant type with large spikes (described previously), and advances in biotechnology (discussed later). Chemical hybridization agents induce male sterility and allow for rapid development of hybrids. They were first considered unacceptably toxic, until recent technological advances reduced their toxicity. The US Environmental Protection Agency has approved the use of one CHA, Genesis®, for hybrid wheat development, making hybrid research more attractive. Private ownership of the chemical may impede its wider use, however.

Current efforts at CIMMYT are targeted towards exploiting heterosis and developing hybrids using CHAs. Together, increased grain filling and heterosis could shift the yield frontier of the new plant germplasm by 15–20%. The breeding program's ability to develop heterotic combinations of the new plant material will be established within 3–5 years, although the actual development and dissemination of hybrids will take perhaps 10 years. An *ex ante* assessment of the economic, social, and institutional impediments, including intellectual property rights, to hybrid wheat development and dissemination is urgently required.

Improving Yield Stability

Aside from breeding for yield potential, research programs should simultaneously invest in breeding for resistance to biotic stresses, quality characteristics, and tolerance to abiotic stresses in the regions they target. Safeguarding and protecting yield potential through breeding for resistance to biotic and abiotic stresses is an important basis for stable yields and wide adaptation. In breeding wheat for high-potential environments, researchers should emphasize developing resistance to biotic stresses (e.g., diseases and pests). Many breeding programs fail to deliver suitable high-yielding cultivars to farmers simply because the cultivars are susceptible to emerging pathogens or become susceptible soon after their release.

Conventional breeding for improved host-plant resistance. In its research to develop desirable levels of disease and insect resistance, CIMMYT combines "shuttle breeding," "hot spot" screening, and multilocational testing within Mexico and abroad to obtain resistance to multiple diseases for the different wheat mega-environments (Dubin and Rajaram 1996). "Shuttle breeding" is a method in which generations of plants from the same crosses undergo alternate cycles of selection in environmentally contrasting locations to combine desirable characters. "Hot spots" are locations where significant variability for a pathogen exists. In these locations, plants can be screened in the presence of the broadest possible range of virulence genes and their combinations. This screening, together with multilocational testing, increases the probability of developing cultivars with durable resistance.

During the last 40 years, considerable genetic progress has been achieved in developing host-plant resistance in wheat to leaf rust, stripe rust, septoria leaf blotch, fusarium head scab, and bacterial leaf streak in high-rainfall areas of the tropical highlands. Some progress has also been made in achieving resistance to diseases of secondary importance, such as barley yellow dwarf, tan spot, and septoria nodorum blotch (Dubin and Rajaram 1996). For decades, breeders have sought to ensure that each new elite cultivar and breeding line possesses a wide range of genes for resistance to pests and diseases. Breeding programs are challenged by the fact that genetic variation is not confined to the host plant but is also a feature of the pest or parasite. With certain types of resistance, selection for a resistant population of the host is closely followed by natural selection of the pest or parasite for those variants that can overcome the resistance. To keep ahead of evolving and changing pest populations, breeders must constantly aim to increase genetic diversity against pests and develop cultivars with more durable resistance.

Wide crossing. Much of the recent effort to enhance the diversity of wheat breeding pools and improve yield stability centers on wide crossing, a technique for introducing desirable genes from wild species into cultivated varieties. For wheat, the *Triticum* grass species are an important source of enhanced genetic diversity, especially goat grass (*Triticum tauschii*) (Mujeeb-Kazi and Hettel 1995). Perennial grasses such as *T. tauschii* can provide a wide range of genetic resistance/tolerance to several biotic/abiotic stresses, appear to be a potent source of new variability for important yield components, and enhance yields in bread wheat.

At CIMMYT, wide crosses between elite durum wheats and *T. tauschii* yielded synthetic hexaploid wheats, which are used extensively in the bread wheat hybridization program. CIMMYT has produced 620 synthetic hexaploids, and an elite subset of 95 has been prepared and partially characterized for morphological traits, yield components, growth, and resistance/tolerance to several biotic and abiotic stresses. All synthetic hexaploids are cytogenetically stable.

Seed size and weight tend to be very much above average in the synthetics. Major gains in yield and yield stability should come from using synthetic hexaploids as parent material in the production of hybrid wheat, primarily because they will help limit the effects of biotic and abiotic stresses. Under conditions in Mexico, synthetic hexaploids have shown diversity for resistance and/or tolerance to more than ten stresses. For example, resistance to Karnal bunt, septoria tritici blotch, fusarium head scab, and spot blotch from synthetic hexaploids is used for bread wheat improvement based on disease screening data obtained over several years. The resistant synthetic hexaploids have been crossed with elite cultivars, and the resulting lines express diversity for resistance to these diseases. Synthetic hexaploids have also contributed to diversifying the genetic base of resistance/tolerance to important abiotic stresses such as heat, drought, waterlogging, and frost at flowering.

Contributions of biotechnology to breeding for yield stability. New biotechnology tools have the potential for considerably increasing the effectiveness and efficiency of wheat breeding programs, providing insights into the genetic control of key traits and markers for manipulation, methods for introducing novel sources of genetic variation, and methodologies for speeding up the breeding cycle (Snape 1996). In the short to medium term, however, the greater contribution of biotechnology will not be to raise yields so much as to improve yield stability by generating plants with improved resistance to pests and tolerance to abiotic stresses.

By facilitating gene selection, ***molecular marker technology*** increases the efficiency with which specific desirable genes are combined into improved breeding lines. Markers are especially useful in breeding for resistance to nonendemic diseases and pests or for incorporating genes with overlapping effects that can contribute to complex and more durable resistance. They are also desirable for working on traits that are expensive to measure, for certain quality-related characteristics, and for traits that are heavily influenced by environmental fluctuations. Marker-assisted selection may also help identify heterotic groupings of parent germplasm, making the rapid development of hybrid wheat lines possible (Jordaan 1996).

Sorrells (1996) has observed that markers are generally cost effective for only those traits that are difficult or costly to evaluate and are controlled by a few genes. The costs of developing and using molecular markers are still relatively high compared to the costs of conventional selection methods, but they are gradually declining.

Although markers should play an increasing role in resistance breeding, there are few examples of markers used for selection in applied wheat breeding programs (McIntosh 1998). CIMMYT uses marker-assisted selection to develop resistance to barley yellow dwarf (BYD), one of the most widespread and damaging viral diseases of wheat. Lines containing genes for BYD resistance introgressed from a wild relative of wheat (*Thinopyrum intermedium*) are being tested in the greenhouse and the field, but resistance levels are not yet satisfactory. *Thinopyrum*-derived resistance genes may also be combined with known and widespread BYD-tolerance genes from other sources, in the hope that the cumulative effects of these genes will confer an acceptable level of BYD resistance. Preliminary results indicate that resistance and tolerance can be combined, resulting in fewer disease symptoms and reduced yield losses.

Plant genetic engineering (crop transformation) is a process for identifying and incorporating genes for valuable traits into a specific crop. These genes, which may originate from any living organism, virus, or even chemical synthesis, are introduced into recipient cells and, preferably through incorporation into the chromosomal DNA, create a new plant with the desirable traits. Transformation offers breeders new opportunities to improve the efficiency and stability of production and increase the utility of agricultural crops.

Agronomically viable levels of durable resistance in crops against a relatively broad range of fungi, such as the pathogens that cause rust diseases, might be achieved using transformation approaches that include insertion and expression of genes encoding inhibitors of fungal enzymes or known antifungal proteins. Antifungal genes have been transformed into a range of crop species, including tobacco, tomato, canola, and rice, and the insertion of such genes into wheat would provide plant breeders with additional sources of resistance.

Wheat transformation research at CIMMYT has two objectives: first, to obtain durable resistance to a range of fungal pathogens, and second, to raise the level of expression of seed storage proteins in wheat endosperm through the introgression of genes for high-molecular-weight glutenin subunits. The unique bread-making characteristic of wheat flour is closely related to the elasticity and extensibility of the gluten proteins stored in wheat starchy endosperm.

Before transformation technology can be fully utilized to develop new cultivars, and before those cultivars can be adopted at the farm level, several procedural and policy issues need to be addressed. A major uncertainty is the regulatory framework governing the release of genetically engineered products, particularly because of growing concern about the public health and environmental safety implications of genetically modified organisms (GMOs). Substantial work has to be done to clarify the environmental and human health impacts of GMOs. Farmers' eventual access to genetically modified cultivars also depends on a large-scale public awareness program addressing the concerns of everyone involved in the current debate on GMOs. Intellectual property protection and plant breeders' rights may further limit access to materials developed through biotechnology. In developing countries, substantial policy reforms that allow for the legal enforcement of intellectual property rights should be in place before the products of biotechnology research are widely available.

CIMMYT's strategy to achieve durable rust resistance in wheat. As noted, the long-term aim of wheat improvement at CIMMYT is to produce germplasm characterized by stable, high yields and possessing durable resistance to various parasite complexes. Genetic manipulation of resistance genes over the last 40 years has enabled wheat plants to hold their own against mutating pathogens of some previously devastating diseases, including *Puccinia graminis tritici* (stem rust) and *P. recondita tritici* (leaf rust), resulting in partial to good stability of resistance. The current importance of the rust diseases in several spring wheat mega-environments[2] is shown in Table 6.

In the 1950s and early 1960s, breeders generally sought to incorporate the hypersensitive (race-specific)[3] type of resistance into wheat. This approach was attractive because the cleanliness of the

Table 6. Current importance of leaf, stem, and stripe rust diseases of wheat in spring wheat mega-environments (MEs)

ME	Leaf	Stripe	Stem
ME1: Favorable	High	Medium	Low
ME2: High rainfall	Medium	High	Low
ME3: Acid soils	High	Low	High
ME4: Semiarid	Medium	Medium	Low
ME5: Tropical	High	Low	Low
ME6: High altitude	High	Low	Low

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[2] One or more of the rust diseases (leaf rust, stem rust, or stripe rust) are the most economically important diseases in many wheat production environments (Byerlee and Moya 1993).

[3] Race-specific resistance, controlled by major genes having large effects, is easily detected with a specific race of pathogen (pathotype). In wheat rust pathosystems, this resistance is recognized by its characteristic low infection type. Numerous genes for race-specific resistance are now known and have been catalogued by McIntosh, Hart, and Gale (1995). Detection of these genes requires either seedling evaluation or testing at post-seedling growth stages.

crop was preserved and it was simple to incorporate resistance into improved germplasm. However, the protection afforded by race-specific genes (or combinations of them) eroded quickly, leaving scientists to look for alternative approaches.

In the late 1960s and 1970s, the concept of general (race-nonspecific)[4] resistance and its application in crop improvement was revived (Caldwell 1968) and widely used to breed for rust resistance in wheat (Borlaug 1968, 1972; Caldwell 1968). This concept, commonly known as slow rusting,[5] has dominated CIMMYT's efforts to breed for leaf rust resistance in bread wheat for more than 25 years and is being used to develop resistance to yellow rust as well.

Since wheat varieties derived from CIMMYT germplasm are grown over large areas and may be exposed to pathogens under conditions that favor the development of disease, CIMMYT has sought to use germplasm sources for rust resistance that are as diverse as possible. The flow of germplasm to and from the bread wheat improvement program is continuous, and CIMMYT scientists are constantly in touch with collaborating research programs to ensure this exchange. Although multilocational testing is not a perfect system for identifying diverse sources of resistance, it helps to confirm the existence of genetic diversity in CIMMYT's germplasm, to understand the genetic basis of resistance, and to judge the performance of regionally important advanced breeding materials against pathogen variation occurring in diverse environments. Genetic studies suggest that wheat genotypes that are resistant to a given rust disease in many locations—as indicated by low average coefficients of infection (ACI)—often contain multiple major or minor resistance genes.

Table 7 shows the phenotypic diversity for resistance to leaf, stripe, and stem rusts of 280 advanced bread wheat lines included in the 24th International Bread Wheat Screening Nursery (IBWSN). Marked differences among phenotypes suggest the existence of different groups of varieties whose response to rust could be subject to different genetic control mechanisms. Progress in breeding for leaf and stem rust resistance has been significant, given that approximately 60% of the IBWSN entries have ACI values of less than 5. However, much more progress remains to be achieved in stripe rust resistance, since only about 10% of the entries had such low ACI values.

Genetic diversity and durability are the two most important features of the disease resistance that CIMMYT researchers seek to incorporate into their wheat lines. Because proof of enduring disease resistance comes only after supposedly resistant cultivars are deployed over a large area, it is important that these cultivars be genetically diverse to ensure against vulnerability. Data on the historical performance of cultivars with different kinds of resistance can help identify sources of durable resistance. Genetic analyses of this resistance could aid in its directed transfer and in the search for genes that could contribute to new gene combinations for durable resistance.

Table 7. Phenotypic diversity in 280 advanced lines of the 24th International Bread Wheat Screening Nursery classified into average coefficients of infection (ACI) for three rust diseases in international multilocational testing, 1990

		Number of entries in ACI classes					
Disease	Number of locations	0–5	5.1–10	10.1–20	20.1–30	30.1–40	> 40
Leaf rust	39	168	78	32	2	0	0
Stripe rust	16	26	62	104	71	15	2
Stem rust	15	162	52	60	4	2	0

Enhancing Input Use Efficiency

The profitability of wheat production systems in favorable environments does not depend on wheat improvement research alone. Crop management technologies that enhance input use efficiency are essential. Achieving sustained growth in wheat productivity while at the same time conserving the resource base will require wheat production increases to be achieved with a less than proportionate increase in input use. Changes in fertilizer application practices, especially the timing and method of application, could significantly reduce nutrient losses and improve plant nutrient uptake. Efficiency gains made through improvements in fertilizer management may contribute to a reduction in the overall fertilizer requirements for sustaining productivity growth.

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[4] Race-nonspecific resistance operates against all pathotypes. This type of rust resistance, based on the additive interactions of several genes having minor to intermediate effects, is usually complex and relatively difficult to identify.

[5] Slow rusting is a type of resistance in which rust develops slowly, resulting in intermediate to low disease levels against all pathotypes (Caldwell 1968). Partial or incomplete resistance is characterized by a reduced rate of epidemic development despite a high or susceptible infection type (Parlevliet 1975).

Today, nearly all strategies to implement sustainable crop management practices involve efficient fertilizer application methods, integrated pest management practices,[6] conservation or zero tillage, and crop residue management (Sayre 1998). Improved land management practices also contribute to enhanced efficiency of water use. Mechanization of land preparation as well as harvest and post-harvest activities will lead to improved labor productivity and the ensuing gains in labor use efficiency.

Improved nitrogen use efficiency. Since the 1950s, successive CIMMYT wheat releases have shown either increasing yield stability, higher mean yields, or both (Traxler et al. 1995). Compared to tall varieties, leading varieties based on CIMMYT germplasm have also required smaller and smaller amounts of land and nitrogen to produce the same amount of wheat (Figure 3; CIMMYT 1996). The implication is that these varieties will enable farmers to release more land for alternative uses and avoid possible overapplication of nitrogen.

The adaptation and performance of CIMMYT bread wheats under low levels of nitrogen have been questioned because these wheats were developed under medium-high levels of nitrogen fertility. To address this doubt, CIMMYT conducted a study to: 1) compare the performance of a set of tall and a set of semidwarf CIMMYT cultivars widely grown by farmers in northwestern Mexico under low and high nitrogen fertility levels; 2) measure the genetic progress in grain yield and nitrogen use efficiency (NUE); and 3) evaluate the contribution of nitrogen uptake efficiency (UPE) and utilization efficiency (UTE) to NUE (Ortiz-Monasterio et al. 1997). Genetic gains in both grain yield and NUE from 1950 to 1985 were 1.1, 1.0, 1.2, and 1.9% per year on a relative basis, or 32, 43, 59, and 89 kg/ha/yr on an absolute basis when plants were provided with 0, 75, 150, and 300 kg/ha of N, respectively. Progress in NUE resulted in improved uptake and utilization efficiency. The relative importance of these two components was affected by the level of applied nitrogen, however. A shift in the wheat yield frontier could lead to further gains in uptake and utilization efficiency.

Improved timing and application of nitrogen fertilizer also confer significant improvements in uptake efficiency. Field experiments indicated a marked increase in nitrogen uptake efficiency and higher yields if fertilizer was applied when wheat plants began to pull nitrogen rapidly from the soil (about 35–45 days after wheat emergence in northwestern Mexico) (Ortiz-Monasterio 1997). These improvements in NUE result in increased grain protein levels and dramatically enhanced baking quality and nutritional characteristics. Nitrogen losses into the environment are also significantly reduced, along with farmers' production costs.

Farmers' adoption of this and any other nitrogen application practice will depend on the ratio of the wheat price to the nitrogen price. When this ratio becomes smaller because wheat prices fall or nitrogen prices rise, the incentive for adopting efficiency-enhancing technologies increases. Liberalization of the agricultural sector in developing countries could be expected to increase the adoption of technologies that increase nitrogen efficiency.

Raised beds. The furrow-irrigated, reduced-tillage bed-planting system (FIRBS) combines the practice of planting wheat in beds with traditional ridge-tillage technologies. It holds immense potential for improving irrigated wheat-based cropping systems by making them less resource-intensive and more sustainable (K.D. Sayre, CIMMYT, pers. comm., 1997). The use of reduced tillage and crop residue management enhances the physical, chemical, and microbiological properties of the soil. Planting wheat on beds provides easy

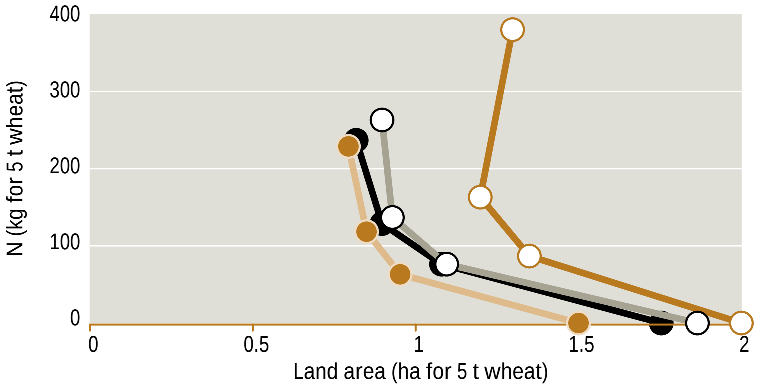

Figure 3. Kilograms of nitrogen required to grow 5 t of wheat. From right: *Tall*, two tall cultivars of 1950 and 1960; *1960s*, three semidwarfs of 1962–66; *1970s*, three semidwarfs of 1971–79; and *1980s*, two semidwarfs of 1981 and 1985.
Source: Calculated by Waggoner (1994) from data in Ortiz-Monasterio et al. (1997).

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[6] Almost no pesticides are used to produce wheat in developing countries.

field access, allowing better opportunities to apply nitrogen fertilizer when and where the wheat plant can use it most efficiently. These options are not readily available for conventionally planted wheat.

The use of mechanical cultivation between the beds is of real value for more integrated weed control, especially where herbicide-resistant weed species are prevalent. In terms of water management, furrow irrigation offers important savings in water use and, in conjunction with the ameliorating effects of crop residues, can improve soils where salinization occurs. The reduction in tillage, combined with the presence of crop residues in irrigation furrows, retards sediment movement in the water, thus reducing siltation of waterways.

Improvements in fertilizer use efficiency, weed control practices, and irrigation management result in markedly better production efficiencies and cost savings for farmers. Reduced tillage practices further reduce production costs and can dramatically shorten turnaround time between crops to ensure more timely planting. Estimates from trials in northwestern Mexico place annual production costs for the new FIRBS technology at nearly 30% less than for current, conventional tillage practices (CIMMYT 1997a).

Enhancing Wheat Productivity in Marginal Environments

Even if the anticipated productivity gains in the high–potential environments become a reality, the projected growth in demand for wheat from the present to 2020 may not be met. Gains in wheat productivity must also be sought in the lower potential, more marginal environments. Low-potential environments for wheat production include: the semiarid areas where drought stress is a problem during the wheat growing season; high temperature environments; and problem soil areas, especially areas with acid soils (see the box, "Wheat Mega-Environments Defined," p. 4). Four arguments are commonly used to support the allocation of research resources to marginal environments (Byerlee and Morris 1993):

- Returns to research may now be higher in marginal environments than in more favorable environments, because the incremental productivity of further investment targeted at favorable environments is declining.
- A large number of people currently depend on marginal environments for their survival, and increasing population pressure is forcing more people into these areas.
- Because the people who live in marginal environments are often among the poorest groups of the population, increased research investment in these areas is justified on grounds of equity.
- Many marginal environments are characterized by a fragile resource base. A special effort is needed for these areas to develop appropriate technologies that will sustain or improve the quality of the resource base over the longer term.

Given these arguments, to what extent should the research system be concerned with technological development in marginal environments? If the international wheat price continues to decline, countries that are integrated into global trade will need to rely less on domestic wheat production. If global wheat prices rise with trade liberalization, then countries will have an incentive to invest in less favorable environments. Given the uncertainty of long-term price trends, the prudent strategy for developing countries is to have a modest level of investment in research for marginal environments. It is important to continue giving greater weight to research investments in favorable environments, because significant positive spillovers from technical change in favorable environments benefit poor people in marginal environments through lower food prices, increased employment, and higher wages (David and Otsuka 1992). These spillovers may actually exceed the positive benefits generated through research targeted specifically at marginal environments (Renkow 1991).

Research investments would be cost-effective in marginal areas where spillover benefits from favorable environments are high. Drought-tolerant germplasm, for example, is derived from crossing high-yielding wheats with wheats traditionally grown in drought-prone areas. Wheat production in West Asia and North Africa has benefited substantially from such spillover research. The international wheat research system plays a crucial role in maximizing the spillover benefits of research on unfavorable environments across countries. Maredia (1993) and Maredia and Byerlee (1999) estimated a "spillover matrix" based on data from CIMMYT's International Spring Wheat Yield Nurseries (ISWYN) and demonstrated that global research spillovers for wheat are large (Table 8). They found that varieties bred by national programs for a specific environment possessed a significant yield advantage in that environment compared to varieties bred for other environments. On the other hand, CIMMYT-related wheats showed a significant yield advantage over locally bred materials across several environments, demonstrating wide adaptability and acceptability in developing countries.

What kinds of research for marginal environments are likely to prove cost-effective? The next sections of this report review research initiatives that should receive priority in the effort to improve the productivity and profitability of wheat production in marginal areas and protect the resource base.

Improving Drought Tolerance

It is widely recognized that Green Revolution technology disseminated more slowly in marginal environments, especially semiarid environments affected by low water availability and drought. Spring wheat mega-environments exposed to drought—i.e., those receiving 500 mm of rainfall or less—are MEs 4A to 4C (see the box, “Wheat Mega-Environments Defined,” p. 4). The annual gain in genetic yield potential in drought environments is only about half of that in irrigated, optimum conditions (Rajaram et al. 1997). Twenty percent of the wheat area is affected by drought and usually characterized by extreme poverty. In addition to these chronically drought-prone areas, a growing water scarcity in some irrigated wheat production environments means that the wheat crop is increasingly subject to drought caused by a reduced, less-than-optimum number of irrigations. Enhanced drought tolerance in wheat could lead to improved food security for populations living in marginal areas and help reduce yield variability related to water scarcity in favorable environments.

As noted, the search for improved wheat germplasm that is tolerant to drought has benefited significantly from spillovers from research directed at favorable environments. The strategy for breeding for drought tolerance has been to combine the high yields and input-responsiveness of cultivars developed for favorable environments with the drought tolerance and water-use efficiency of germplasm from semiarid areas. CIMMYT’s Veery lines and the advanced line Nesser are two examples.

CIMMYT’s Veery lines, developed originally for favorable environments in the 1970s and early 1980s, have adapted well to less favorable environments, except for those with rainfall below 300 mm/yr. The Veery wheats essentially are a genetic system that combines high yield performance in favorable environments and adaptation to drought. The Veerys demonstrate that efficient input use and responsiveness to improved levels of inputs (such as available water) can be combined in one plant system and used to produce germplasm for marginal (in this case semiarid) environments. Because most semiarid environments differ significantly in annual precipitation distribution, and because water availability also differs across years in these environments, it is prudent to construct a genetic system in which plant responsiveness provides a bonus whenever higher rainfall improves the production environment. With such a system, improved moisture is immediately translated into greater yield gains for farmers (Calhoun et al. 1994; van Ginkel et al. 1998).

Table 8. Relative yield performance of wheat cultivars of different origins in various mega-environments (MEs), 1980– 89

	ME where varieties are tested[a]						
	1 Irrigated	2 High rainfall	3 Acid soils	4A Winter rain	4B Winter drought	5A High temperature	6 High latitude
1 Irrigated	1.00	0.95	0.84	0.90	0.88	1.02	0.94
2 High rainfall	0.95	1.00	0.81	0.92	0.90	0.89	0.96
3 Acid soils	0.89	0.96	1.00	0.85	0.90	0.98	1.00
4A Winter drought	0.99	0.94	0.78	1.00	0.83	0.91	0.93
4B Early drought	0.90	0.97	0.89	0.91	1.00	0.90	0.99
5A High temperature	0.88	0.86	0.92	0.82	0.89	1.00	0.92
6 High latitude	0.88	0.89	0.84	0.87	0.91	0.84	1.00
CIMMYT/Mexico[b]	1.11	1.13	0.99	1.01	1.07	1.01	0.98

Source: Maredia and Byerlee (1999); see also Maredia (1993) and Maredia and Eicher (1995).

Note: Off-diagonal values less than one indicate that directly introduced wheat varieties from other mega-environments yield less than those developed by local breeding programs in the test ME. Similarly, values greater than one (as in the case of CIMMYT varieties) indicate that directly introduced wheat varieties from these sources yield more than those developed by local breeding programs in the test ME.

[a] Yield expressed relative to the yield of varieties originating in that ME =1.00.

[b] Varieties derived from CIMMYT crosses and released in Mexico.

By the mid-1980s, CIMMYT-bred germplasm occupied 45% of the semiarid wheat area receiving between 300 and 500 mm/yr of rainfall and 1% of the area receiving less than 300 mm/yr (CIMMYT 1992), including large tracts in West Asia and North Africa. By 1990, 63% of the dryland area was planted to semidwarf wheats (Byerlee and Moya

1993), many carrying the Veery parent material. A recent progeny of Veery that combines adaptation to optimum and stressed conditions is Baviacora.

Nesser, an advanced line showing superior performance under drought conditions, has been popular in the semiarid environments of West Asia and North Africa and is considered by the International Center for Agricultural Research in the Dry Areas (ICARDA) to represent a unique, drought-tolerant genotype (ICARDA 1993). Bred by CIMMYT in Mexico in favorable environments, Nesser carries the combination of input efficiency and high yield responsiveness described earlier and performs similarly to the Veery lines.

Considering this evidence and the general failure of traditional breeding methods to deliver superior, widely adapted wheat germplasm for semiarid environments, combining input efficiency and input responsiveness appears to be a rational operational methodology for breeding drought-tolerant wheats. This methodology is supported in recent research publications (Bramel-Cox et al. 1991; Cooper, Byth, and Woodruff 1994; Duvick 1990, 1992; Edhaie, Waines, and Hall 1988; Uddin, Carver, and Cutter 1992; Zavala-García et al. 1992) which indicate that testing/selecting in a range of environments, including well-irrigated ones, has proven effective for identifying superior genotypes for stressed conditions.

As hybrid wheats are developed, their performance under drought conditions ought to be more closely examined. Both hybrid maize and hybrid rice have exhibited superior performance under low-rainfall conditions because of their greater rooting depth (CIMMYT 1997b; Virmani 1999). Spillover benefits to drought-prone areas from hybrid wheats developed for high-potential areas may be significant.

Improving Heat Tolerance

In tropical wheat areas, high temperatures are usually a problem during the growing season. In Upper Egypt and central Sudan, for example, high temperatures, especially during grain filling, can drastically reduce wheat production. Because high temperatures indirectly reduce yield by affecting various yield components, yield remains the most reliable yardstick for selecting cultivars that tolerate heat stress (e.g., in yield trials). In segregating populations, however, yield cannot be deployed as a salient criterion because a large, unmanageable number of lines would have to be harvested, threshed, and the grain weighed. CIMMYT Wheat Program researchers and others employ a combination of empirical observation and quantitative measurement to select bread wheats that tolerate heat stress.

When thousands of lines are deployed in segregating populations, an experienced plant breeder can make subjective but fundamentally correct judgments on biomass, number of spikes, tillering capacity, stand establishment, leaf senescence, and grain-filling period. This empirical judgment should be supported by properly analyzed yield trials and quantitative measurements to substantiate the associations of characters involved in heat stress tolerance (Morgounov 1995). New data indicate that canopy temperature depression is a useful criterion in selecting for heat tolerance (Reynolds et al. 1994; M. van Ginkel, CIMMYT, pers. comm.). When leaf temperature is less than the ambient air temperature, the plant is more likely to be tolerant to heat stress. AbdElGhani, AbdElShafi, and Ghanem (1994) also found that efficient screening for heat stress can be done through multilocational testing (including sites in different countries with similar environments) and through using different planting times to create heat stress environments. These techniques enabled them to select varieties tolerant to heat stress in Upper Egypt and Sudan, such as El Nelain, Giza 160, Giza 164, and Debeira. Moderate success in breeding for heat stress has been reported in other countries as well. Bangladesh has released Kanchan and Sonalika, and UP-262 has had widespread acceptance in eastern India.

Coping with Acid Soils

On approximately 1 billion hectares in the tropics and subtropics, soil acidity limits plant growth. This area includes large parts of Brazil, the Andes, China, Southeast Asia, the Himalayas, and East/Central Africa. Soils of high-rainfall regions where forests or savannas were once the native vegetation are also usually acidic. Many of these areas have either not been developed for agriculture, or, where cultivated, are of very low productivity. The incidence of diseases affecting cereal crops in such environments is frequently high because of high levels of precipitation and humidity. Excess aluminum and/or manganese ions in the soil, along with disease pressure, at one time restricted the performance of CIMMYT germplasm in acid soil areas (Kohli and Rajaram 1988).

Although wheat area and production were expanding in Brazil throughout the 1960s and into the early 1970s, the country did not enjoy the benefits of the "miracle" semidwarf Mexican varieties that were creating a Green Revolution elsewhere. The foremost limitation on the adaptation of semidwarf wheats to Brazil was their extreme susceptibility to toxic levels of aluminum and manganese, compounded by the phosphorus deficiency in the acid soils of the region.[7]

Despite heavy applications of industrial lime to neutralize the acidic effects of the soil, aluminum toxicity remained a serious problem for Mexican germplasm sown in parts of Brazil in the late 1960s. Brazilian wheat varieties tolerated the effects of aluminum toxicity and diseases, even though these varieties had low yield capacity and tall, weak straw. In the mid-1970s, CIMMYT entered into a collaboration with Brazilian scientists to combine Brazilian wheats' tolerance to aluminum toxicity with the Mexican wheats' semidwarf stature, high yield potential, and wide adaptation. More than a decade of research yielded semidwarf wheats with aluminum tolerance. The new aluminum-tolerant Brazilian varieties had a yield potential that was 30% higher than that of the old varieties under Brazilian conditions. In addition to high yield potential, the new Brazilian germplasm had improved rust and mildew resistance; a better agronomic type with regard to plant type, shorter and stronger straw, and larger, more fertile spikes; and better heat and drought tolerance. CIMMYT germplasm gained longer leaf duration, aluminum tolerance, increased phosphorus uptake efficiency, and resistance or tolerance to the leaf spotting diseases.

CIMMYT distributes outstanding advanced lines emanating from this shuttle project to 50 locations worldwide. Based on data from these multilocational tests, outstanding lines for yield, aluminum toxicity tolerance, and agronomic type are fed back into the crossing program to further pyramid favorable genes into better cultivars. As a result, a number of high-yielding, aluminum-tolerant wheat cultivars have been released or recommended for release in several Brazilian states, and promising cultivars have been developed for other countries with soil acidity problems. The cooperative shuttle program and distribution of the resulting materials has begun providing benefits to countries in other regions, such as Madagascar, Zambia, Kenya, Tanzania, Rwanda, Cameroon, and Ecuador.

Meeting the Unresolved Challenges for Marginal Environments

At least three related factors help explain the relatively slow rate of progress in marginal environments compared to more favorable areas (Morris, Belaid, and Byerlee 1991). First, the climate in dryland production zones severely constrains the yield potential of cereal crops, so the impact of improved seed-fertilizer technologies is bound to be less dramatic than in the more favorable environments where these technologies are highly successful. Second, investment in agricultural research targeted at rainfed areas has been modest, in part because such research was perceived as having a lower potential payoff. Third, largely because of the first two factors, many countries have been slow to implement policies that would promote cereal production in rainfed areas, such as policies to develop market infrastructure.

Despite those factors, and contrary to the common perception that the problems of unfavorable environments have received inadequate attention, wheat research and cultivar development have been fairly successful in these environments. The principle of maximizing spillover benefits has worked exceptionally well in generating germplasm for drought-prone and acid soil environments. Even so, some large challenges remain to be faced: drought stress in environments where there is no rainfall during the growing period or in environments where rainfall levels are below 300 mm/yr; the need to combine drought tolerance with heat tolerance; nutrient deficiencies (boron and zinc); and salinity. Further success in marginal environments depends on a substantial effort to develop germplasm and target it appropriately to particular settings.

Although modern varieties may play some role in boosting yields in marginal areas, germplasm will usually not be the main stimulus for rapid technical change, as is the case in favorable areas. Marginal environments would benefit more substantially from improvements in crop and resource management technologies, which often precede changes in variety (as has already happened in Turkey) (Morris, Belaid, and Byerlee 1991). For example, given that moisture is the primary constraint in the marginal environments, the primary

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[7] It later became clear that soil acidity affected not only Brazil but also many wheat-growing regions of Africa and Asia.

emphasis of technological innovation ought to be moisture conservation and improvements in moisture use efficiency. Diversification of crop and enterprise systems is also an important means of enhancing and/or sustaining incomes in marginal environments, so more effort will be needed to improve wheat productivity in marginal environments where yields remain well below potential. However, prospects for future gains in productivity, as well as promising research strategies, will differ somewhat between regions. All of these circumstances suggest a larger role for research on crop and soil management relative to breeding research, as well as some reorganization of research and extension strategies (Morris, Belaid, and Byerlee 1991).

Implications for Global Wheat Research

Given that growth in population and income will continue to spur a steady rise in wheat demand, the challenge for sustaining wheat productivity growth is great. Production increases will be needed in favorable as well as marginal production environments. While the need for wheat productivity growth is great, it is not clear that the past high level of government investment in wheat research and technology development will be sustained. Here we discuss the combination of global trends, research strategies, and emerging trends in research and development that will shape the global wheat improvement system in the years to come and ultimately influence supply and demand for wheat.

Global Trends

The anticipated global integration of food markets and rapid urbanization make it less likely that governments will give the same emphasis to self-sufficiency in food crop production as in the past. Greater integration of the global food economy will lead to fundamental changes in food policies as developing nations move away from traditional self-sufficiency goals and towards increased emphasis on comparative advantage. Some countries may deliberately redirect agricultural research resources away from cereal crops to higher value commercial crops, especially countries with smaller populations that find it feasible to purchase a significant portion of their food requirement on the international market.

As the proportion of the world's population living in urban areas comes to exceed the rural-based population in the 21st century, provisioning the cities will become the key strategic goal of developing country governments. Governments will face an increasingly dichotomous situation of rising urban demand for cereals and declining supplies. Supplies will decline because of a net movement of resources out of the agricultural sector, especially labor, and increasing levels of diversification out of cereal crop production into higher value fruit and vegetable crops. Under the circumstances, exclusive reliance on domestic cereal crop production may not be prudent for most governments. In the case of wheat, with the exception of large producers such as China, India, Argentina, Pakistan, Turkey, and Iran, most countries should attempt to strike a balance between domestic production and imports to maintain urban bread prices at an affordable level. Since large urban centers are frequently located in coastal areas, costs of transporting grain from overseas are often lower than the costs of transporting grain from within the country.

In addition to globalization and urbanization, increasing scarcity of land, labor, and water resources, along with the removal of input subsidies, will make cereal crop production, particularly wheat and rice, less profitable at the farm level (Pingali, Hossain, and Gerpacio 1997). To sustain farmers' interest in wheat production, the research system needs to focus on reducing unit production costs by shifting the yield frontier and/or increasing input use efficiencies.

Research Strategies for Favored and Marginal Environments

While germplasm enhancement will continue to be the cornerstone of the strategy for increasing productivity growth, innovations in crop and resource management will become increasingly important for favorable and marginal environments from a productivity as well as from a sustainability perspective. In favorable environments, the emphasis ought to be on enhancing input use efficiency, especially for fertilizer, water, power, and human labor. In the marginal, low-rainfall environments, the emphasis of crop and resource management research ought to be on moisture conservation and efficiency of water use.

For favored environments, shifting the yield frontier while enhancing disease resistance is the priority for wheat genetic improvement. Since wheat germplasm for favorable environments has a high rate of spillover across national boundaries, the rational strategy for wheat improvement research would be for all but the large wheat-producing countries to rely on international germplasm flows and restrict domestic development of cultivars to adaptive breeding. Even the large wheat-producing countries should continue to use the international germplasm exchange system as a source of advanced lines and diverse materials for their crossing programs.

In the case of marginal environments, improved tolerance to physical stresses will continue to be the priority for wheat research. To a large extent, productivity growth in the marginal environments will have to come from technology spillovers from the high-potential environments. Only in the case of specific abiotic stresses, such as drought or high temperature, will the research system have to set up a targeted research program. A full-scale breeding program for marginal wheat-growing environments will be profitable only in countries such as China, India, Brazil, and Argentina, which have large areas that are marginal for wheat production. Other countries would continue to rely on the international germplasm exchange system.

Emerging Trends in Research and Development

The big breakthroughs in crop breeding research in the 21st century are likely to come from new applications of science to the traditional problems of shifting the yield frontier and enhancing yield stability. Recent advances in biotechnology, especially gene mapping and genetic engineering, should significantly increase the supply of wheat germplasm with durable resistance to diseases and improved tolerance to physical stresses. An improved understanding of plant physiology and crop modeling should also help breeders' efforts to shift the wheat yield frontier and develop alternative crop management strategies.

The application of new scientific tools to plant breeding will require intensive collaboration between developed country universities, advanced research institutions, international centers, and national research systems. The spillover benefits from the application of new tools to crop breeding should be high, and many developing countries may choose to benefit from spillovers rather than invest in full-fledged scientific capacity to produce new products themselves. The size of the wheat area will be a primary factor determining whether particular countries will invest in biotechnology and other new wheat improvement technology.

The level of private sector participation in wheat research and development will also have a bearing on the activities of the global wheat improvement system. In research and cultivar development for pure-line cereals (wheat, rye, triticale, rice, oats, and barley) and grain legumes in developing countries, the private sector has yet to play an active role. In research on hybrid cereals (maize, sorghum, and millet), where investments are protected by trade secrecy, the private sector has taken the lead in genetic enhancement and cultivar development. The role of the private sector in hybrid maize production in developing countries has been expanding rapidly. Hybrid wheat, when it becomes available, is expected to generate a similar level of interest from the private sector. Finally, although the private sector plays a very considerable role in biotechnology research, in some countries the lack of intellectual property protection could dampen the private sector's enthusiasm for participating in cereal crop research and development.

Intellectual property rights and their implications for the flow of genetic material can also be expected to transform the way the global wheat improvement system operates. The wheat revolution would not have progressed as rapidly as it did without the free and widespread global exchange of germplasm and information. International spillovers of research results, and the consequent economies of scale that resulted from the global flow of genetic resources, enabled wheat-growing countries both large and small to benefit from investments in wheat research. Future success in disseminating wheat technology worldwide depends on the continued uninhibited flow of genetic material and information. Restrictions imposed on such movement by intellectual property protection could have serious consequences on developing countries' ability to sustain growth in wheat productivity.

Part 2

Assessing the Benefits of International Wheat Breeding Research: An Overview of the Global Wheat Impacts Study

Paul W. Heisey, Mina A. Lantican, and H. Jesse Dubin

In 1990, CIMMYT conducted a study to evaluate the impacts of international wheat breeding research in the developing world from 1966 to 1990. Its objectives were to provide information to researchers on the acceptance or rejection of new technologies and the underlying reasons for adoption or nonadoption, and to demonstrate the benefits of wheat research for those who fund it (Byerlee and Moya 1993).

In 1997, CIMMYT's Economics and Wheat Programs launched a follow-up survey to update the data and analysis of the first study. Specifically, the second study sought to:

- document the use of CIMMYT-related and other improved wheat germplasm;
- document the farm-level adoption of improved wheat germplasm;
- identify factors that affect adoption of modern varieties (MVs);
- generate information for setting research priorities; and
- provide information to raise awareness of the importance and benefits of international wheat research.

Questionnaires were sent to the 41 developing-world countries that produce more than 20,000 t of wheat annually.[1] Responses were received from 36 countries, representing just under 99% of all wheat production in the developing world. On a regional basis, coverage ranged from 94% of production in West Asia/North Africa to nearly 100% in Latin America (Table 1). The latest study differs from its predecessor in several respects. It includes South Africa for the first time, and there is more complete coverage of China's wheat area.

Table 1. Regional coverage for global wheat impacts study, 1997

Region	Coverage (% of total wheat production)
Asia	99.7
Sub-Saharan Africa	98.3
West Asia and North Africa	94.3
Latin America	Nearly 100

This second part of our report presents preliminary results of the global wheat impacts study. The first section analyzes global wheat improvement research by national agricultural research systems (NARSs) and provides a measure of research intensity. The second section presents the pattern of release of wheat varieties over time and the use of wheat germplasm from CIMMYT. The third section presents data about varieties currently grown in farmers' fields and compares different measures of CIMMYT's contribution to those varieties. This preliminary assessment of the achievements of the international wheat research system concludes with a discussion of several issues that impinge upon the future effectiveness of the system.

Wheat Research Efforts by NARSs

Studies conducted in the early 1990s by Bohn and Byerlee (Bohn and Byerlee 1993; Bohn, Byerlee, and Maredia 1999) and updated more recently by CIMMYT found that research intensity, measured as the number of scientists per million tons of wheat production, tended to fall with increasing wheat production (Figure 1). This appears to be an empirical regularity: because of the inverse relationship between production level and research intensity in the developing world, small wheat-producing countries tend to have a high intensity of wheat improvement research. The resulting implications for research efficiency, particularly for small research programs, have been considered by Maredia and Byerlee (1999).

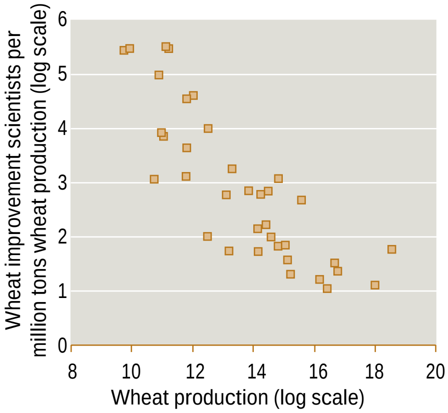

Figure 1. Wheat production and scientists per million tons of wheat production, developing countries, 1997.
Source: CIMMYT wheat impacts database.

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[1] Note that the Central Asian and Caucasus states were not included in either study.

Analysis based on the actual numbers of scientists involved in wheat improvement research must be treated with considerable caution, given the inherent constraints of an impersonal questionnaire and the difficulty of enumerating scientists outside of the national research program who conduct research related to wheat improvement (e.g., researchers in universities). These factors could lead to an underestimate. On the other hand, both the 1990 and 1997 surveys asked respondents to identify the number of full-time equivalent scientists involved in wheat breeding, even when they represented disciplines other than plant breeding. In some instances, this could lead to an overestimate of the effort devoted to wheat improvement research, as opposed to, for example, wheat crop management.

In terms of the number of scientists per million tons of wheat production, wheat research intensity across the developing world appears to be slightly greater near the end of the 1990s than it was earlier in the decade: 6.2 scientists per million tons in 1997 compared to 5.3 in 1992–93 (Bohn and Byerlee 1993) (Figure 2).

This difference arose largely because a greater number of wheat improvement scientists were reported for China in 1997. When China is excluded, the 1992–93 and 1997 figures are nearly identical.

Based on these figures, wheat research intensity may appear to be fairly stable, but it is important to note that research by the International Food Policy Research Institute (IFPRI) and the International Service for National Agricultural Research (ISNAR) has suggested that financial support for agricultural research in many NARSs has fallen in recent years. This trend has been masked at the aggregate level by continued support for research in strong national research systems such as China and India. Funding for wheat improvement research by NARSs appears to be increasingly polarized, with large wheat-producing countries continuing to support research while many smaller countries allocate fewer and fewer resources to national wheat research.

Releases of Wheat Varieties

The national research systems of developing counties released about 2,200 wheat varieties between 1966 and 1997. Of these, about one-fourth were released in 1991–97. The rate at which varieties are released, as measured by the number of varieties released per million hectares per year, seems to have increased in recent years in several regions (Figure 3). Variability in rates of release in some countries over time was particularly striking, despite the use of five-year moving averages to smooth out short-term fluctuations.

During the past 30–40 years, wheat varieties have been released at a much higher rate in Latin America and sub-Saharan Africa than in the rest of the developing world. Higher rates of release may be associated with smaller wheat areas, greater diversity in mega-environments (that is, in the target environments for wheat research; see "Wheat Mega-environments Defined," p. 4), the rate at which disease complexes change, and greater participation of the private sector in wheat improvement.

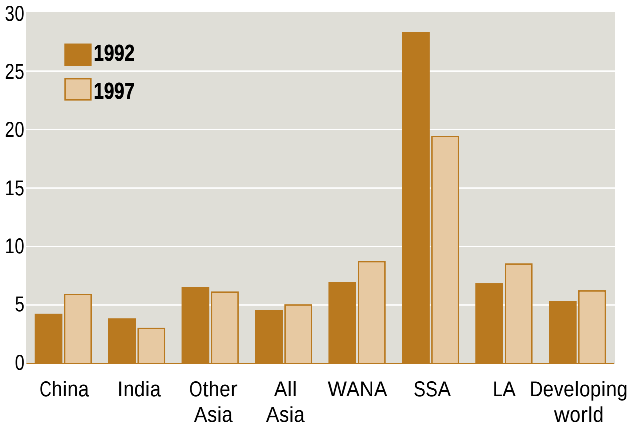

Figure 2. Wheat improvement scientists per million tons of wheat production, developing countries and regions, 1997.
Source: CIMMYT wheat impacts database.
Note: WANA= West Asia/North Africa; SSA= Sub-Saharan Africa; LA= Latin America.

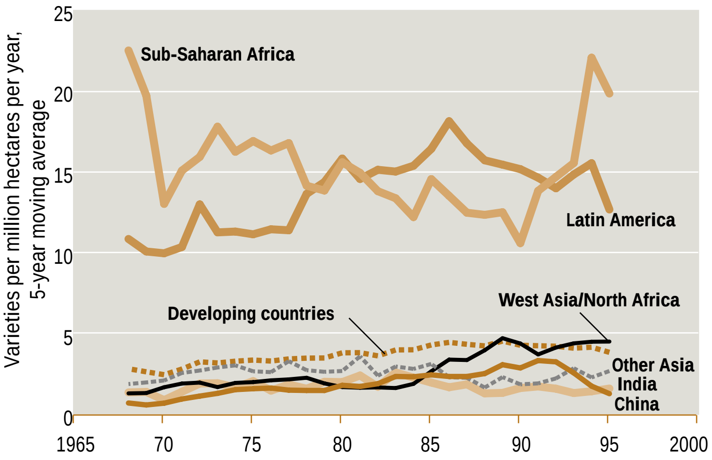

Figure 3. Rate of release of wheat varieties, 1960s–1990s.
Source: CIMMYT wheat impacts database.

Although the public sector dominates wheat improvement research in developing countries, there are some exceptions. Private-sector wheat improvement research has been strong in Argentina for some time. Varieties developed by the private sector are also sown in Brazil and Uruguay, and Chile conducted some private-sector wheat research in the past. In Africa, the private sector currently appears to be important in South Africa and Zimbabwe (Heisey and Lantican 1998). Other African countries, such as Kenya and Zambia, which had no private-sector wheat researchers in 1990, reported a modest level of private-sector research activity by 1997. Across the developing world, however, less than 4% of the wheat area is planted to private-sector varieties, and most of these varieties are based on germplasm developed by the public sector.

All of the countries surveyed have made considerable use of CIMMYT wheat germplasm. China differs from most of these countries, however, by using its own material to a great extent. The extent to which the Indian and Brazilian wheat improvement programs used their own crosses was also notable, although a substantial amount of the breeding material in the Indian and Brazilian research programs was based on CIMMYT germplasm (Traxler and Pingali 1998). In most other countries, the importance of CIMMYT crosses and CIMMYT parents has not changed since the 1990 study.

Nearly all **spring bread wheats** released by NARSs in developing countries are semidwarfs. The pattern of spring bread wheat releases over time is reported in Figure 4. Of the 357 spring bread wheats released by national research programs between 1991 and 1997:

- 56% were CIMMYT crosses, sometimes with reselection by NARSs;
- 28% were NARS crosses with at least one CIMMYT parent;
- 5% were NARS crosses with CIMMYT ancestry;
- 8% were NARS semidwarfs with other ancestry; and
- 3% were tall varieties.

The percentage of spring bread wheat releases that were CIMMYT crosses or had at least one CIMMYT parent in 1991–97 (84%) was higher than in the earlier study period, indicating that the use of CIMMYT germplasm has not declined in recent years.

Compared with spring bread wheats, a higher proportion of **spring durum wheats** released by NARSs contained CIMMYT germplasm (Figure 5). Between 1991 and 1997, of 52 spring durum wheats released by national programs:

- 77% were CIMMYT crosses;
- 19% were NARS crosses with at least one CIMMYT parent;
- 2% were NARS crosses with known CIMMYT ancestry; and
- 2% were tall varieties.

Spring durum releases based on CIMMYT crosses were predominant in West Asia/ North Africa and Latin America.

Of 106 **winter/facultative bread wheats** released by national programs in 1991–97:

- 19% were CIMMYT crosses;
- 13% were NARS crosses with at least one CIMMYT parent;
- 9% were NARS crosses with known CIMMYT ancestry;
- 41% were NARS semidwarfs with other ancestry; and
- 18% were tall varieties

Figure 6 presents winter/facultative bread wheat releases in the developing world by time period. The number of releases was considerably higher in 1991–97 than

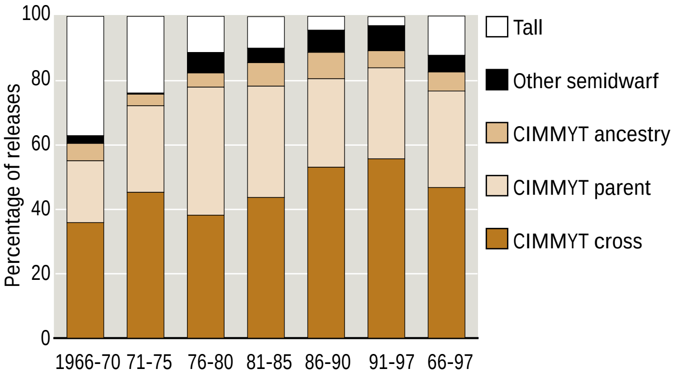

Figure 4. Spring bread wheat releases by time period, developing world.
Source: CIMMYT wheat impacts database.

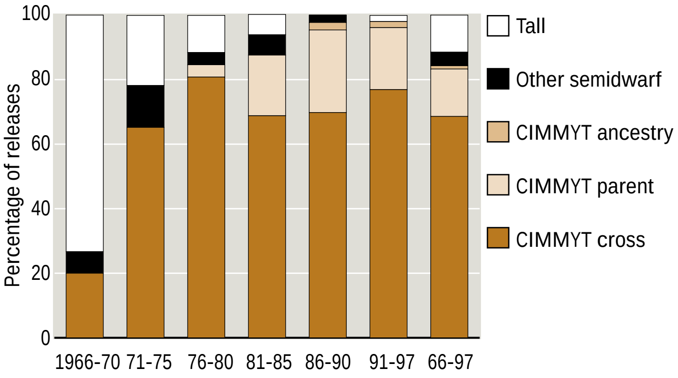

Figure 5. Spring durum wheat releases by time period, developing world.
Source: CIMMYT wheat impacts database.

in the previous study period, particularly in West Asia/North Africa. The percentage of winter/facultative releases that contained CIMMYT germplasm was also considerably higher in 1991–97 than before. Non-CIMMYT winter/facultative semidwarfs were mostly Chinese releases.

Table 2. Area (million hectares) grown to different wheat types in 1997, classified by the origin of the germplasm

		National research system cross						
Wheat type	CIMMYT cross	CIMMYT parent	CIMMYT ancestor	Other semidwarf	Tall	Landraces	Unknown cultivars	All
Spring bread wheat	17.8	22.4	12.6	7.7	5.2	1.4	1.0	68.1
Spring durum wheat	3.4	1.2	0.02	0.11	0.3	1.5	0.1	6.7
Winter/facultative bread wheat	0.6	1.9	4.2	11.6	2.2	4.1	2.6	27.2
Winter/facultative durum wheat	0.0	0.0	0.0	0.1	1.0	0.1	0.0	1.2
All wheat types	21.8	25.5	16.8	19.5	8.7	7.0	3.8	103.2

Source: CIMMYT wheat impacts database.

Adoption of Improved Wheat Varieties

Slightly more than 80% of the wheat area in the developing world is planted to semidwarf varieties (Figure 7). Sixty-two percent of the wheat area in the developing world is estimated to be planted to varieties with CIMMYT ancestry. Slightly less than half of the wheat area is planted to varieties produced from crosses made by CIMMYT or that have at least one CIMMYT parent. The proportion of wheat area planted to CIMMYT-related material is greater for spring bread and spring durum wheats than for winter/facultative wheat. Table 2 summarizes the area planted to different wheat types in 1997.

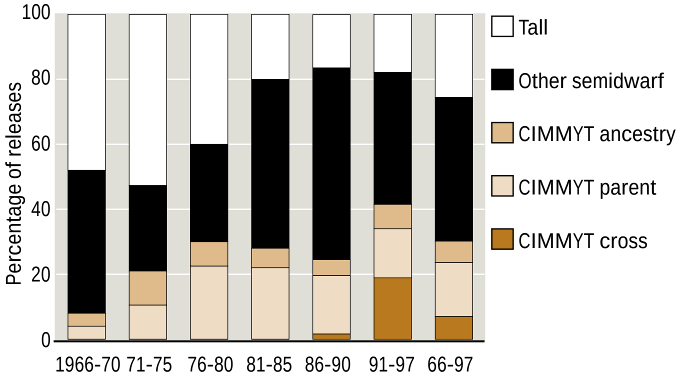

Figure 6. Winter/facultative bread wheat releases by time period, developing world.
Source: CIMMYT wheat impacts database.

Spring Bread Wheat

Spring bread wheat is the dominant type of wheat grown in the developing world. Nearly 68 million hectares of the developing world wheat area (including China) was planted to spring bread wheat in 1997. Of this area, about 60 million hectares were planted to semidwarfs, nearly 53 million hectares (88%) of which were sown to CIMMYT-related varieties. CIMMYT crosses or NARS crosses with at least one CIMMYT parent occupied about 40 million hectares.

The adoption of CIMMYT-related spring bread wheat in 1997 is shown for regions of the developing world in Figure 8. Excluding China, 80–90% of the spring bread wheat area in the

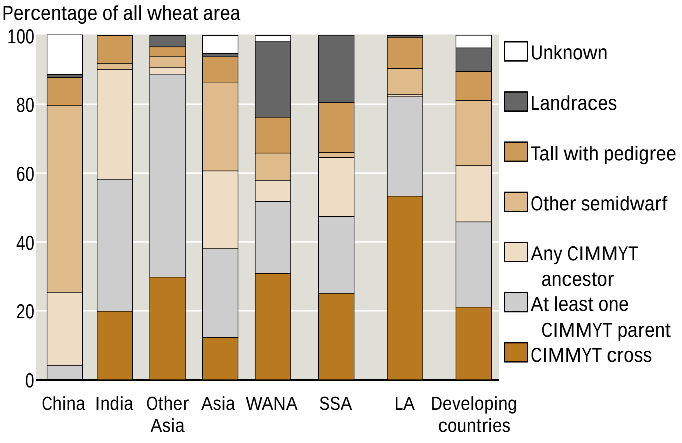

Figure 7. Area planted to all wheat in developing countries, 1997.
Source: CIMMYT wheat impacts database.
Note: WANA= West Asia/North Africa; SSA= Sub-Saharan Africa; LA= Latin America.

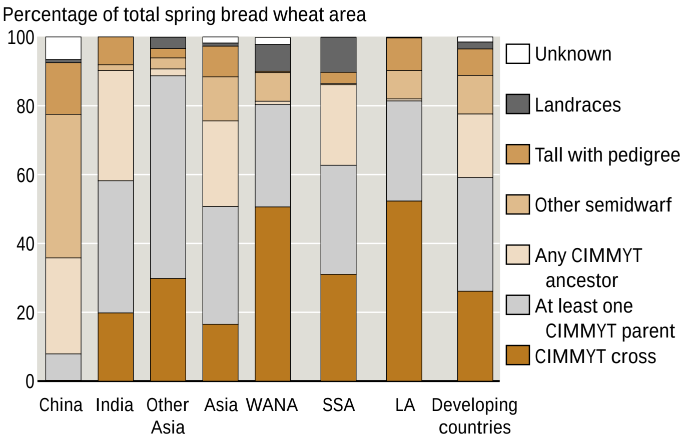

Figure 8. Area planted to spring bread wheat in developing countries, 1997.
Source: CIMMYT wheat impacts database.
Note: WANA= West Asia/North Africa; SSA= Sub-Saharan Africa; LA= Latin America.

developing world's major wheat growing regions was planted to CIMMYT-related material. The use of CIMMYT crosses was greatest in West Asia/North Africa and Latin America, where more than 50% of the spring bread wheat area was planted to CIMMYT crosses. In China, about one-third of the spring bread wheat area was planted to CIMMYT-related germplasm, and an additional 40% was planted to semidwarf wheats that did not contain CIMMYT germplasm.

Spring Durum Wheat

Spring durum wheat area, which is relatively small compared to area sown to other wheat types, is predominantly sown to semidwarfs, primarily CIMMYT-related varieties. As was the case with adoption of spring bread wheats, Latin America and West Asia/North Africa were the major adopters of CIMMYT crosses in spring durum wheat. More than 50% of the spring durum wheat area in West Asia/North Africa, where over 80% of the developing world's durum wheat is grown, was planted to CIMMYT crosses. In Latin America, the percentage of area planted to CIMMYT crosses was more than 90% (Figure 9).

Winter/Facultative Bread Wheat

In contrast to spring bread wheat and spring durum wheat regions, areas planted to winter/facultative bread wheat are dominated by semidwarf wheats that are unrelated to CIMMYT wheats. Among the regions where winter/facultative bread wheat is grown, Latin America was the only region where CIMMYT material was dominant (Figure 10). In China, where winter/facultative bread wheat occupies more than half of the wheat area, nearly two-thirds of the winter/facultative bread wheat area (36% of the total wheat area) consisted of non-CIMMYT winter/facultative semidwarfs. In the other region with a large winter/facultative wheat area, West Asia/North Africa, nearly 40% of the winter/facultative wheat area was planted to landraces and another 35% was sown to varieties with some CIMMYT ancestry. In South Africa, which is the only country in sub-Saharan Africa growing winter/facultative wheat, two-thirds of the area was planted to tall varieties with pedigrees (versus tall varieties whose pedigrees are unknown).

Landraces

Relatively little spring bread wheat area remains in landraces. Unlike spring bread wheat, large proportions of both the spring durum wheat area and the winter/facultative bread wheat area were still planted to landraces in 1997. Seven million hectares of the developing world's wheat area were sown to landraces and 3.8 million hectares were planted to unknown cultivars (i.e., their pedigrees and origin were unknown).

Landraces tended to be concentrated geographically in West Asia/North Africa. Landraces covered slightly less than 20% of the spring durum area in West Asia/North Africa. In Ethiopia, the only country in sub-Saharan Africa where durum wheat is planted, landraces covered nearly 80% of the wheat area. As noted, landraces occupied nearly 40% of the winter/facultative wheat area in West Asia/North Africa.

CIMMYT/NARS Collaboration

The data for numbers of released varieties and area planted indicate that CIMMYT plays a major role in wheat improvement research for developing

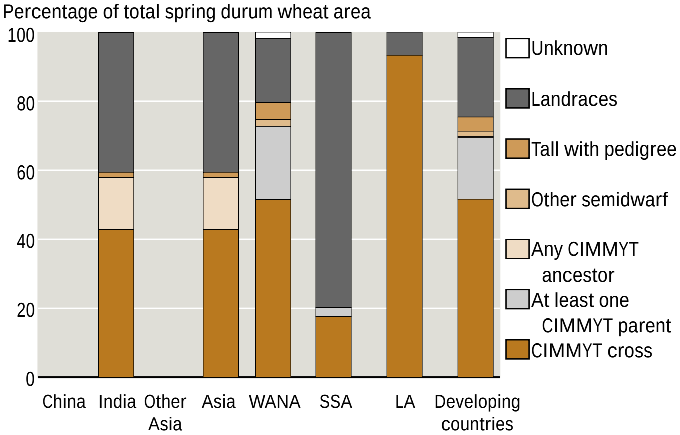

Figure 9. Area planted to spring durum wheat in developing countries, 1997.

Source: CIMMYT wheat impacts database.
Note: WANA= West Asia/North Africa; SSA= Sub-Saharan Africa; LA= Latin America.

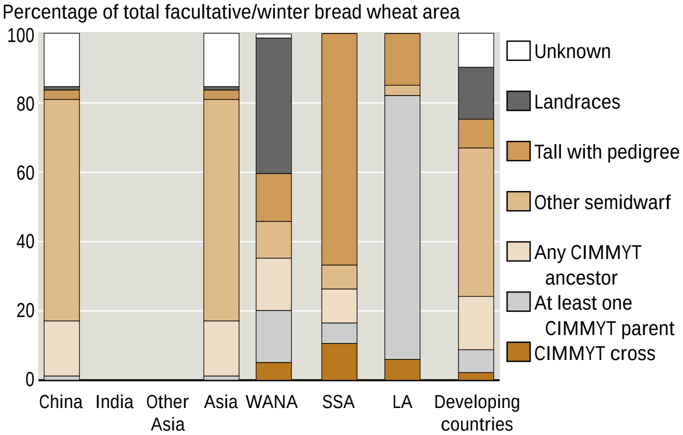

Figure 10. Area planted to facultative/winter bread wheat in developing countries, 1997.

Source: CIMMYT wheat impacts database.
Note: WANA= West Asia/North Africa; SSA= Sub-Saharan Africa; LA= Latin America.

countries. It is important to recall that the Center's contribution is not the result of independent activity; international wheat improvement research is collaborative and progress depends on international testing by a network formed by CIMMYT and national research systems worldwide (Maredia and Byerlee 1999). Furthermore, every cross is the result of a conscious decision by the breeder and institution that made the cross, of decisions made earlier by other breeders, and ultimately of breeding decisions made by the farmers who tended landraces over the centuries.

Trends and Observations

The extensive data collected for the 1990 and 1997 studies allow us to look for longitudinal trends, albeit using a rather short time frame. Our estimates of wheat area have relied on fairly simple ways of assessing the CIMMYT contribution. Here, we recapitulate some of those measures and present an additional one based on a geometric rule developed by Pardey et al. (1996). This additional measure analyzes a variety's pedigree by applying geometrically declining weights to each level of crossing for as many generations as desired. The weights applied to the earliest generation included in the analysis are increased to make the total of all weights sum to 1.[2]

For comparison, we present estimates for 1990 based on the data analyzed by Byerlee and Moya (1993). In presenting the 1997 data, we provide figures that both include and exclude China, because only a few spring bread wheat zones in China were covered in the 1990 study and because China does not use CIMMYT germplasm as extensively as other developing countries. Calculations for spring bread wheat are presented in Figure 11 and for winter/ facultative bread wheat in Figure 12.[3]

Excluding China, spring bread wheat area planted to CIMMYT crosses declined between 1990 and 1997. During the same time, however, area planted to NARS crosses with CIMMYT parents increased, as did the area planted to spring bread wheat with any CIMMYT ancestry. The decline in spring bread wheat area planted to CIMMYT crosses can be explained by somewhat lower planting of direct CIMMYT crosses in India, Turkey, and Pakistan—three large developing-country wheat producers. By the geometric rule, in 1990, approximately 45% of the genetic contribution to spring bread wheat could be attributed to CIMMYT. In the 1997 data, this figure fell to slightly more than 40%, because of the decline in area planted to CIMMYT crosses (as crosses are given the most weight in the geometric index).[4] As expected, when China is included the CIMMYT contribution declines by all measures; the decline is proportionately the lowest when using the "any ancestor" rule (Figure 11). The reason for this finding is that, compared to other breeding programs, the Chinese wheat program often uses CIMMYT material at an earlier stage of the crossing process.

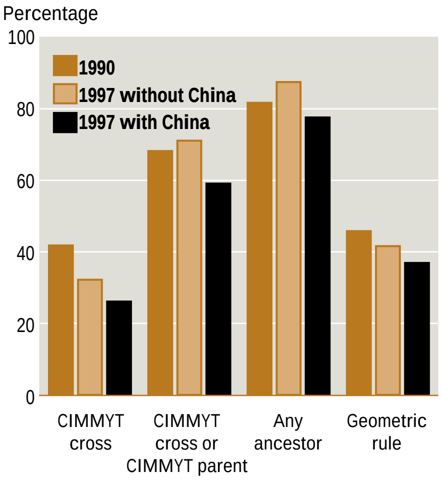

Figure 11. CIMMYT contributions to spring bread wheat planted in developing countries, 1997.
Source: CIMMYT wheat impacts database.

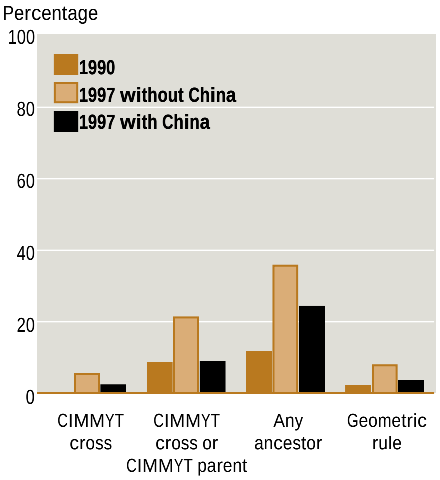

Figure 12. CIMMYT contributions to winter/ facultative bread wheat planted in developing countries, 1997.
Source: CIMMYT wheat impacts database.

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[2] For example, if the analysis were carried back to the level of great-grandparents, the source of the final cross would be given a weight of 1/2, the source of each of the parents would be given a weight of 1/8, and the source of each of the grandparents would be given a weight of 1/32. The next fraction in this series is 1/128, but the source of each of the great-grandparents would be given a weight of 1/64 to ensure that the weights sum to 1.

[3] Calculations for spring durum wheat are being revised. As a result, estimates for spring durum wheat and for "all wheat" are not presented; however the patterns for spring durum and all wheat are fairly clear.

[4] Although the estimates for spring durum wheat are being recalculated, it is likely that in comparison with spring bread wheat, CIMMYT crosses are more important in terms of area planted in spring durum than in spring bread wheat; NARS crosses with at least one CIMMYT parent, and NARS crosses with earlier CIMMYT ancestry, are less important in durum wheat. Genetic contribution as measured by the geometric rule is greater in spring durum wheat than in spring bread wheat, again because of the higher weight given to the final cross. Slightly more than 50% of the genetic contribution to spring durum wheat planted in developing countries would be attributed to CIMMYT by this rule.

As expected, the data on releases and area planted show that CIMMYT has made a smaller contribution to winter/facultative wheat breeding in developing countries relative to its contributions to spring bread or spring durum wheat breeding. Even so, CIMMYT's contribution to winter/facultative wheat has grown substantially since 1990. No CIMMYT winter/facultative crosses were planted in 1990; in 1997, a small area was planted to such crosses. Excluding China, the proportion of winter/facultative wheat planted to varieties with some CIMMYT ancestry tripled between 1990 and 1997 (Figure 12). Within China in 1997, a little more than 10% of the winter/facultative wheat area was planted to a variety with some CIMMYT ancestry.

The final figures for all wheats taken together are not yet available, but they will most likely parallel the estimates for spring bread wheat, because that is the dominant wheat type in the developing world. It then follows that the area planted to CIMMYT crosses is likely to have declined somewhat between 1990 and 1997, while the area planted to NARS varieties with at least one CIMMYT parent and to NARS varieties with earlier CIMMYT ancestry increased. By the geometric rule, it appears that in 1990 *and* 1997 CIMMYT accounted for just under 40% of the genetic contribution to all wheat planted in the developing world (excluding China). If China is included, the 1997 CIMMYT contribution would probably be less than 30%.

Outstanding Issues

In assessing the impacts of international wheat breeding research in the developing world, several issues merit further study and analysis. These include the rate at which varieties are replaced in farmers' fields, the rates of genetic gain in wheat yield and yield gain in farmers' fields, and the future of international collaboration in wheat improvement research.

Varietal Replacement

Our most recent data indicate that, as reported in the 1990 study by Byerlee and Moya (1993), a significant proportion of the total wheat area is still planted to older improved varieties. Despite the fact that farmers in developing countries have widely adopted improved varieties, the rate at which older improved seed is replaced by seed of newer improved varieties remains unacceptably slow. Farmers benefit neither from the improved yield potential of newer varieties nor from their superior disease resistance.

One measure of the rate at which varieties are being replaced is the age of varieties in farmers' fields, measured in years since release and weighted by the area planted to each variety (Brennan and Byerlee 1991). Based on this indicator for 1990 and 1997, varietal replacement had become more rapid by 1997 in only 12 of the 31 countries for which comparisons could be made.

Table 3 presents a classification of countries by weighted average age of improved varieties in farmers' fields in 1997. Note that only improved varieties (semidwarfs and improved tall varieties) are included in these calculations. Among developing countries, only two, Zimbabwe and Afghanistan, had an average age of varieties in farmers' fields within less than six years. This length of time is important because it is the period estimated (based on weighted averages) in which rust resistance derived from a single resistance gene can be maintained (Kilpatrick 1975). (Rust is the most important disease of wheat worldwide; for a discussion of the importance of rust resistance, see "CIMMYT's strategy to achieve durable rust resistance in wheat," p. 10.) In Zimbabwe, it appears that the private sector's involvement in wheat research may have played a role in the rapid turnover of wheat varieties. In Afghanistan, external aid following the Russian withdrawal included widespread distribution of wheat seed.

Most Latin American countries, with the exception of Peru and Mexico, seem to replace their varieties in the field more rapidly than other developing countries, which is consistent with earlier findings (Byerlee and Moya 1993). In Mexico, however, varietal replacement was much more rapid in the past (Brennan and Byerlee 1991), primarily because of a shift in the major wheat-growing areas of northwestern Mexico from bread wheat to older durum wheat varieties.

Table 3. Weighted average age (years) of improved varieties in farmers' fields, 1997

Country	Age of varieties
Afghanistan, Zimbabwe	<6
Argentina, Brazil, Chile, China, Guatemala, Pakistan	6–8
Bolivia, Columbia, Iran, Nigeria, Uruguay, Zambia	8–10
Ecuador, Morocco, Paraguay, South Africa, Tanzania	10–12
India, Kenya, Lebanon, Mexico, Syria, Yemen	12–14
Algeria, Bangladesh, Ethiopia, Egypt, Jordan, Nepal, Peru, Sudan, Tunisia, Turkey	>14

Source: CIMMYT wheat impacts database.

In contrast to Latin America, in most nations of West Asia/North Africa the weighted average ages of varieties in the field exceeded 14 years. Interestingly, even some large wheat-producing countries such as India had weighted varietal ages exceeding 12 years, although wheat varieties were replaced much more rapidly in some regions of India, particularly the northwest (Byerlee and Moya 1993). Factors affecting the rate of varietal replacement in wheat are discussed from a theoretical perspective by Heisey and Brennan (1991) and empirically by Heisey (1990) and by Mwangi and colleagues (see, for example, Alemu Hailye et al. 1998; Regassa Ensermu et al. 1998; and Hailu Beyene, Verkuijl, and Mwangi 1998).

Genetic Gains in Wheat Yields and Yields in Farmers' Fields

Considerable debate has surrounded the question of whether breeders are continuing to make genetic gains in yield potential in the major cereals or whether most recent progress has come from raising the bottom of the yield distribution by increasing resistance to stress (see Evans and Fischer, forthcoming; Mann 1999). It appears that the genetic yield potential of wheat has continued to increase (Evans and Fischer, forthcoming; Sayre, Rajaram and Fischer 1997). An extensive review of studies about gains in wheat yields in developed and developing countries also concluded that there is no convincing evidence that genetic gains in wheat yield potential have leveled off (Rejesus, Heisey, and Smale 1999). As is apparently the case in rice and maize, in wheat the larger proportion of genetic gains in yield also results from increased stress tolerance rather than gains in yield potential *per se*. Much of the progress in developing stress tolerance in wheat has come from dramatically improved resistance to wheat diseases, particularly the rusts (Sayre et al. 1998).

Meanwhile, there is ample evidence that yield advances in farmers' wheat fields have slowed. Worldwide, some of this slowdown may be partially explained by reduced growth in demand for wheat, but it is noteworthy that yield increases in advanced wheat-producing areas of developing countries (e.g., northwestern Mexico and the Punjabs of India and Pakistan) have also slowed in the past 10–15 years. The reasons for slower growth in yield gains in farmers' fields are many and complex; it is quite likely that crop management issues and resource degradation play important roles (see Part I of this report for a discussion of the opportunities and constraints related to improving wheat productivity).

The Future of International Collaboration in Wheat Improvement Research

During the 1990s, the framework and dynamics of crop improvement research entered a period of rapid change. Increased private-sector investment in crop improvement, changes in intellectual property rights regimes, and potential technical changes came together to alter the ways that breeders and farmers can use seed. These developments continue to transform the dynamics of germplasm exchange, in some cases limiting the free exchange of germplasm on which the success of the CIMMYT/NARS international wheat breeding effort was built. Although many of these changes are taking place primarily in industrialized countries, it is clear that the impacts will be global.

During this same period, research intensity for wheat breeding in the developing world seems to have increased, as has the rate at which wheat varieties are released. Despite these indicators of progress, ancillary evidence on the funding and organization of wheat research in all but a few of the largest NARSs and in CIMMYT's own wheat program suggests that the international system for wheat improvement research faces continuing challenges in the years ahead.

The structure and organization of the international wheat breeding effort was discussed in Part I of this report and has been extensively analyzed by Maredia and Byerlee (1999), Byerlee and Traxler (1996), and Traxler and Pingali (1998). It is clear from these analyses and from the data presented here that the CIMMYT/NARS collaborative effort in wheat improvement could remain central to producing significant benefits for wheat-producing nations and farmers well into the next century. Whether the political will and financial resources to sustain that effort will be available, however, remains an open question.

Part 3

The World Wheat Economy, Post-2000: Focus on Asia

Prabhu L. Pingali

Recent projections by the International Food Policy research Institute (IFPRI) indicate that, by 2020, two-thirds of the world's wheat consumption will occur in developing countries, where wheat imports are estimated to double by 2020. As noted earlier in this report, wheat demand worldwide is calculated to rise by 40% from 1993 to 2020 to reach 775 million tons. The expected increase in demand is partly motivated by population growth but also results from substitution out of rice and coarse grain cereals as incomes rise and populations become increasingly based in urban areas.

When countries move from low- to middle-income status, per capita consumption of maize and rice for food declines, while per capita consumption of wheat tends to rise (see "Wheat for Asia's Increasingly Westernized Diets," p. 28).[1] In China for example, wheat consumption is expected to rise from 83 kg per capita per annum in 1993 to 88 kg per capita per annum in 2020 (Rosegrant et al. 1997). India, on the other hand, is expected to see per capita wheat consumption rise from 55 to 64 kg per annum.

Competitiveness of Wheat Production in Developing Countries

Although wheat demand is expected to rise, it is not clear that expanding domestic production will be competitive in many developing countries. The developing world is undergoing unprecedented policy reforms that could significantly affect growth in wheat productivity over the next several decades and significantly influence the level of wheat imports. The reforms fall into two broad categories: liberalization of the agricultural sector and increased global economic integration. As Part I of this report indicated, the primary impact of these reforms is to move developing country agriculture away from its traditional focus on food self-sufficiency. Crop choice and land use decisions will be made increasingly on the principles of comparative advantage rather than on the imperatives of domestic food needs. The nonagricultural sector will compete more strongly for production inputs (even those available on the farm, such as family labor), and these inputs will be valued at their true opportunity cost.

Liberalization of the agricultural sector could imply an almost total removal of policy protection and support to the cereal crops sector. Output price supports, input subsidies, and preferential access to credit will all be gradually phased out or at least substantially reduced. Infrastructural and research support for the cereals sector can also be expected to decline as governments diversify their agricultural portfolios to include crops that are competitive on the global market.

The anticipated liberalization of developing country economies and their increased global integration will have significant consequences for the organization and management of agricultural production. The anticipated withdrawal of labor from the agricultural sector will lead to an increase in the opportunity cost of labor and make smallholders' intensive cereal production systems less profitable relative to other income-earning and livelihood opportunities. Land and water resources will face similar competitive pressures from the nonagricultural sectors. Provisioning food for the growing urban conglomerates is expected to be a major challenge of the 21st century, but it is important to recognize that domestic sources of supply will have to compete with often cheaper international sources of supply, especially in coastal mega-cities.

Even with the anticipated success in enhancing growth in wheat productivity, the quantity of wheat imported into the developing world is expected to increase. Traditional wheat exporters, such as Argentina, Australia, Canada, and the US would definitely benefit from the increased global demand, and new exporters are expected to emerge in Latin America and Africa. Countries with high land-to-labor ratios, good market infrastructure, and suitable agroclimatic conditions are all candidates to expand wheat exports. Brazil and Mexico are two countries to watch in this regard. Mexico is already emerging as an important player in the export market for durum wheat.

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[1] At very high income levels, per capita wheat consumption also tends to fall.

Special Report:

Wheat for Asia's Increasingly Westernized Diets

Prabhu L. Pingali and Mark W. Rosegrant

The increasing Westernization of Asian diets (in other words, the substitution out of rice and increased consumption of bread and high-value foods) is an inevitable consequence of rising incomes, urbanization, and economic modernization. The growth in per capita wheat consumption is an excellent indicator of the extent of diet diversification in Asia. Asian wheat demand in 2020 is projected to be around 322 million tons as compared to 205 million tons in 1993. The current economic downturn in Asia is anticipated to have only a minimal effect on the extent of diet diversification and per capita wheat demand.

Most countries of East and Southeast Asia can meet their increasing demand for wheat only by importing more wheat. China and the countries of South Asia, however, will not find it economically or politically expedient to rely exclusively on imports for meeting their additional wheat requirements. In these densely populated countries, domestic wheat production will have to increase dramatically to ensure reliable wheat supplies and food security.

Changing Dietary Patterns and Wheat Demand

Across Asia, rapid economic growth and urbanization are creating dramatic changes in dietary patterns. As incomes rise, rice becomes an increasingly inferior good in Asia. Households tend to increase their consumption of bread and high-value food such as meat, poultry products, fruit, and vegetables.

The income elasticity of demand for wheat rises rapidly with income growth as countries move from low to middle income levels; at middle to high income levels, income elasticity of demand remains relatively stable; and at very high income levels, it turns negative. East and Southeast Asian countries fall into all three of these categories, although Japan, with a per capita wheat consumption of 50 kg per year, is the only Asian country exhibiting negative income elasticity of demand for wheat.

The IFPRI IMPACT model (Rosegrant et. al. 1997) projects that Asia will account for 42% of global wheat demand in 2020 as opposed to 37% in 1993. China, with an anticipated demand in 2020 of 152 million tons, and India, with an anticipated demand of 96 million tons, together will account for 77% of Asian wheat demand. According to baseline estimates, Asian demand for wheat is anticipated to grow at least 3% per year through 2020. Even assuming that productivity will grow steadily in Asia's wheat-growing areas, large import volumes are projected (see below).

The current economic slowdown in Asia should have only a modest effect on wheat demand, which is anticipated to be 5% lower than baseline estimates. Reduced growth scenarios were estimated using a 50% reduction in growth in nonagricultural GDP, beginning in 1999, for all Asian developing countries. If the economic downturn were to affect only Southeast Asia and South Korea, the impact on wheat demand would be even more modest. Demand for wheat in 2020 in Southeast Asia and Korea would fall an estimated 800,000 t and 300,000 t, respectively, relative to 2020 baseline projections.

The countries of Southeast Asia are experiencing the most rapid growth in wheat consumption as their incomes rise; it is anticipated that they will have positive and rising income elasticities of demand through the 2020 time horizon. Per capita wheat consumption in the region, which was less than 5 kg/yr in 1961, increased three-fold over a 30-year period, reaching 15 kg per capita per annum by 1993. It is expected to double, relative to its 1993 level, by 2020, despite the economic crisis of 1997.

Wheat demand patterns in South Asia are different from those of East and Southeast Asia. Wheat is the traditional cereal in northern India, Pakistan, Nepal, and northern parts of Bangladesh. Per capita consumption in these areas tends to be relatively stable with respect to income growth; per capita wheat consumption is projected at around 2.8% per annum through 2020. Increasing demand in South Asia will continue to be driven primarily by population growth. Income-induced diversification in diets and the substitution out of rice are observed mainly in southern and eastern India, parts of Bangladesh, and Sri Lanka. Per capita growth in wheat consumption in these areas is projected to be approximately 3.4% per annum through 2020.

Sources of Wheat Supply

Asia's increased demand for wheat will have to be met through a combination of increased imports and enhanced domestic production, where technologically feasible. The technological potential for increasing wheat production is limited in the countries of East Asia (except China) and Southeast Asia, where accelerating demand for wheat will be met primarily through expanding imports. In China, India, Pakistan, Bangladesh, and Nepal, wheat demand will be met though marginal imports and expanded domestic supplies.

Asian wheat imports are expected to escalate rapidly over the next two decades relative to the 1996 level of 30 million tons. IFPRI projects Asian wheat imports will reach 62 million tons by 2010 and 75 million tons by 2020. Asia's current economic downturn is anticipated to have only a modest impact on wheat imports, a drop of five million tons at the most, relative to IFPRI's baseline projection. If China remains unaffected by the Asian economic crisis, the drop in import demand will be a mere one million tons. Despite anticipated growth in domestic supplies, China is expected to import approximately 22 million tons of wheat by 2020. Wheat imports in 2020 to East and Southeast Asia (excluding China) are projected at 24 million tons, a two-fold increase over 1993 levels.

For China as well as India and other South Asian countries, rapid growth in domestic wheat production is absolutely crucial to meeting growing requirements for wheat. Wheat demand in China and South Asia in 2020 will reach 300 million tons, but there are serious concerns regarding the prospects for sufficiently increasing domestic wheat production. These concerns relate to technological opportunities for productivity growth in the favorable and marginal wheat growing environments, to policy issues, and to farm-level incentives for increasing productivity, especially with the increased global integration of food markets.

Special Report:

Wheat in Kazakhstan—Changing Competitiveness and Sources of Productivity Growth

Jim Longmire and Altynbeck Moldashev

Kazakhstan faces many challenges in its transition from a centrally planned economic system towards a more market-oriented one. Like many other former Soviet republics in transition, Kazakhstan experienced a sharp contraction in its economy and high inflation in the years immediately following independence. The overall economic situation has since improved slightly, but the agricultural sector remains particularly affected by the political and economic changes.

One of Kazakhstan's primary responsibilities in the Soviet economy was the production and export of wheat. Wheat is still the country's principal crop, and Kazakhstan remains the dominant wheat producer of Central Asia as well as the third largest producer of the former Soviet republics (following Russia and the Ukraine). Kazakhstan is also the most important producer of high-protein wheat in Asia and Europe.

Wheat production takes place in two predominant environments, the dryland steppes of the north and the irrigated and rainfed southern environment. The northern area is planted to spring wheat varieties owing to its extreme winter conditions and precipitation patterns. Conditions in the southern regions of the country are suitable for producing winter wheat. Spring wheat makes up the overwhelming majority of wheat cultivated in Kazakhstan.

A combination of factors, including macroeconomic policies and policies within the agricultural sector, have precipitated large adjustments in Kazakhstan's wheat economy. The government has drastically reduced its investment in the agricultural sector in favor of increased activity in energy and other extractive sectors, where relatively larger potential exists for foreign exchange earnings and foreign investment opportunities. Decreases in funding and personnel have placed severe constraints on the breadth and scope of research and extension activities that can be carried out. The government has also taken a laissez faire attitude in price policies for both agricultural inputs and outputs.

In response to the existing incentives, dramatic decreases in wheat area, output, and yields have occurred in the last decade (Figures 1 and 2). Wheat area fell from more than 15 million hectares in the late 1980s to slightly over 9.5 million hectares in 1998. Yields have also declined in the last decade,

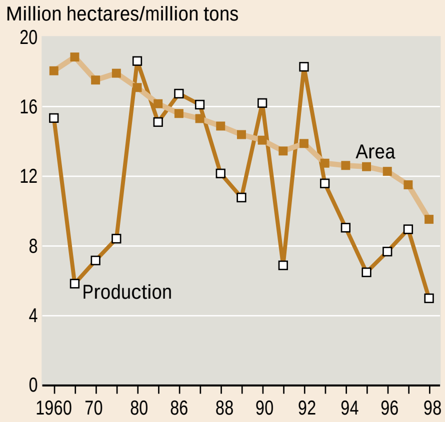

Figure 1. Kazakhstan wheat area and production, 1960–98.

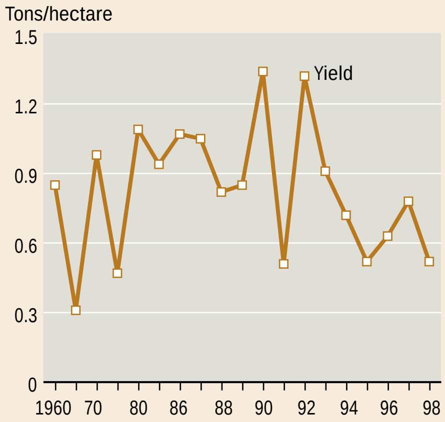

Figure 2. Kazakhstan average wheat yield, 1960–98.

Source: Kazakhstan State Committee for Statistics, FAOSTAT.

dropping from an average of slightly over 1 t/ha between 1985 and 1990 to under 0.7 t/ha between 1993 and 1998. The combined decline in area and yield caused wheat production to fall from an average of 14.5 million tons to less than 5 million tons during the same time period. Farm profitability and incomes have fallen as well, and the level of input use on farm has been considerably reduced (see table). Phosphate use was 315,000 t in 1992 and 55,000 t in 1996. Nitrogen use shows a similar trend, falling from 150,000 t to 63,000 t between 1992 and 1996. Many transactions for inputs and services now commonly rely on bartering.

However, the lack of investment and the decline in public research expenditures have not been the only causes of reduced productivity in the wheat sector. Decades of unsustainable cropping patterns have contributed to degradation of the resource base. Some of the most inappropriate land for wheat cultivation has already been dropped from production.

Table 1. Fertilizer use (000 t) in Kazakhstan

Input	1992	1993	1994	1995	1996
Nitrogen	150	86	65	64	63
Phosphate	315	231	50	25	55
Potash	10	7	6	6	6

Source: FAOSTAT (1998); World Bank (1999).

What are the potential sources of future wheat productivity growth? The inherent challenge of dealing with the variability resulting from climate-induced cropping conditions, particularly in northern Kazakhstan, will always be present. Kazakhstan is fortunate to have a strong tradition of agricultural research. Continued research in wheat improvement and related seed management should lead to greater productivity. Gains from improved disease resistance alone may be substantial. Another promising area of research falls within the realm of agronomy and crop management improvement. Practices such as more timely planting, better moisture management, better weed control, and improved crop rotation have all successfully increased yields in field trials and could possibly provide farmers with a favorable cost/benefit tradeoff.

The present and potential technological possibilities are numerous, but they must be examined in the context of the environment in which farmers operate. The current disincentive to invest in inputs, machinery, and new technologies has major implications for agricultural research and extension. The input-intensive technologies developed during the Soviet era are generally no longer competitive under the developing market-based system. In the next few years at least, farmers are likely to adopt only those methods that will incur minimal costs. Further research in targeting the most useful and cost-efficient technologies at the farm level is needed. Changes, albeit gradual, in farm organization and ownership, will also necessitate adjustments in current extension methods.

Note: For more detail on wheat in Kazakhstan, see Longmire and Moldashev (1999).

Targeting Wheat Research and Development Investments

With the progression towards global integration, the competitiveness of domestic wheat production can be maintained only through dramatic reductions in the cost per ton of production. As discussed in Part I of this report, some of the high pay-off strategies for increasing the competitiveness of wheat, particularly in the high-potential environments, include shifting the yield frontier, increasing yield stability, and enhancing input use efficiencies. Research and development (R&D) in the lower potential environments ought to concentrate on improving yield stability through the development of genetic materials and production systems with improved tolerance to drought and other physical stresses.

The returns to cereal crop R&D investments will not be uniformly high in all countries and all environments. To ensure adequate future grain supplies, it will be crucial to target these investments carefully. Some of the factors that ought to be taken into account in determining the returns to R&D for a particular crop are the size of the domestic market, export potential, and the proportion of high-potential area under the crop.

The size of the domestic market is determined by aggregate population projections as well as by the prospects for income growth. Countries with large populations, such as India and China, would want to invest in improving domestic cereal supplies to buffer the consumer against the vagaries of the international market. The demand for productivity-enhancing technology is generally expected to be the greatest in the high-potential production environments, especially in countries with a large domestic demand for cereals. In the case of wheat, the irrigated environments were the primary beneficiaries of the Green Revolution, and in the short to medium term, sustaining productivity growth in these environments depends largely on sustained R&D investments.

Given the above, where should one expect to see high returns to investment in wheat R&D? China and India are the leading countries for anticipated high returns to investment in wheat R&D, primarily directed towards meeting domestic demand. Mexico, South Africa, and Egypt are also likely to find wheat research investments directed to the domestic market to be attractive (Egypt in particular through spillover benefits gained from other regions of the world). Among wheat exporting countries, the largest gains through such investments, specifically for spring wheats, are likely to be in Australia and Argentina. The open question in the case of wheat is the potential of the countries in the former Soviet Union to respond to global wheat demands through increased exports (see "Wheat in Kazakhstan: Changing Competitiveness and Sources of Productivity Growth").

The foregoing discussion is not meant to imply that countries with smaller wheat growing areas will find their production unprofitable or that they will be unable to benefit from improved technologies. By making modest investments and maximizing spillover benefits from other countries with similar agroclimatic conditions, several of these countries may experience productivity gains similar to those in larger wheat producing countries.

Similar caution ought to be expressed in making R&D investments for marginal environments. Where spillovers from favorable environments are possible, modern varieties do move into marginal environments under appropriate market conditions and generally perform better than traditional varieties. Where spillovers are not possible, and where a shift in the yield frontier is potentially the only source of productivity growth, public research investment will be needed to develop varieties with appropriate tolerance to physical stresses.

The importance of the marginal environment to the domestic cereal sector and the availability of alternative sources of livelihood for people living in that environment are major determinants of the level of public research investment for improving crop productivity. In Sub-Saharan Africa and South Asia, continued high levels of investment in marginal environments are imperative to ensure long-term food security for people living in those areas, in the absence of other livelihood opportunities. Finally, investments in marginal environments cannot be based solely on efficiency criteria: equity considerations will continue to play a major role in investment decisions.

Part 4

Selected Wheat Statistics

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The following tables present statistics related to wheat production, trade, utilization, experimental yield, type of wheat, prices, and input use. These statistics reflect the latest information available at the time of publication.

Countries are classified as either "developing" or "high income" based on the criteria used by the World Bank in its World Development Indicators (1999). Countries classified as "developing" had a per capita GNP lower than US$ 9,655 in 1997, whereas high-income countries had a per capita GNP exceeding US$ 9,656. Countries in Eastern Europe and the former Soviet Union (FSU) are treated separately. Traditionally included as "developed" countries in FAO statistics, most of these countries would be classified as developing countries by World Bank criteria.

The first two sets of tables present production statistics and consumption statistics. Developing countries and those in Eastern Europe and the FSU are included in the individual country statistics if they consumed (or produced) at least 100,000 tons of wheat per year. Developing countries are classified as "wheat producers" if they produced more than 100,000 tons of wheat per year, regardless of import and consumption levels. Developing countries that produced less than 100,000 t/yr, but that produced at least 50% of their total wheat consumption, are also classified as producers. Other developing countries that consumed over 100,000 t/yr are defined as "wheat consumers." High-income countries are classified in the same way, using minimum levels of production or consumption of 1 million tons. A three-year average of the latest data available was used in the classification.

Unless otherwise indicated, the regional aggregates include data from all the countries in a particular region, including those countries for which data have not been reported individually. For a list of countries belonging to each region, see Appendix A. Regional means are appropriately weighted; thus they may not exactly equal the mean of the average values presented for each country. Former Czechoslavakia, former Yugoslavia, and the FSU were divided into separate countries, for which statistics are reported individually.

Notes on the Variables

The data source for all production and consumption statistics is FAO, *FAOSTAT* (1999).

Growth rates were calculated using the log-linear regression model:

$$\ln Y = \alpha + \beta t + \varepsilon,$$

where $\ln Y$ is the natural logarithm of Y, t is time period (year), α is a constant, β is the growth rate of Y, and ε is the error term. The function describes a variable Y, which displays a constant proportional rate of growth ($\beta>0$) or decay ($\beta<0$). β may be interpreted as the annual percentage change in Y.

Yield was computed by dividing three-year average production by the three-year average area harvested, which gives an average weighted by areas in the different years. The data source is the *FAOSTAT Production Statistics* (1999).

Net imports are defined as the amount of imports less exports. The data source is the *FAOSTAT Trade Statistics* (1999).

Total consumption was calculated as the sum (in kg) of the amounts used for each type of wheat utilization (i.e., food, feed, seed, processing, waste, and other uses). The data source is the *FAOSTAT Food Balance Sheets* (1999). The growth rate was calculated using the regression model given above.

Data on wheat type, prices, and input use were collected through a general country survey of knowledgeable wheat scientists. Data for experimental yield come from the CIMMYT Wheat Database Management System, Phenotypic and Genetic Data Tool (WDMSPGD). The data for prices and input use refer to an important producing region within each country. The wheat price is the average post-harvest price received by farmers. The fertilizer price is usually the price paid by farmers for the most common fertilizers. In a few cases, data were estimated by CIMMYT staff based on secondary sources.

Production statistics

	Average wheat area, yield, and production, 1995-97			Growth of wheat area (%/yr)			
REGION / COUNTRY	Harvested area (000 ha)	Yield (t/ha)	Production (000 t)	1951-66	1966-77	1977-85	1985-97 *
Eastern and Southern Africa	2882	1.6	4709	2.1	1.0	0.4	-1.2
Ethiopia	877	1.3	1113	1.0	-5.7	4.0	10.1
Kenya	159	1.9	295	-0.9	-1.1	-0.4	1.4
South Africa	1350	1.7	2328	3.1	3.4	0.9	-4.9
Sudan	302	1.8	539	8.4	13.4	-17.9	12.5
Zambia	18	3.2	57	n.a.	27.6	13.5	12.4
Zimbabwe	50	4.1	204	4.6	19.8	-7.5	0.9
North Africa	6037	2.0	11767	0.0	0.9	-1.1	1.3
Algeria	1595	1.1	1715	0.2	1.5	-3.3	-1.1
Egypt	1039	5.6	5769	-1.8	0.1	-1.1	6.8
Morocco	2558	1.2	3108	0.7	-0.2	0.4	1.8
Tunisia	827	1.4	1144	-1.5	2.8	-0.3	1.2
West Asia	21436	1.8	38220	2.5	1.3	-0.1	0.7
Afghanistan	2025	1.3	2620	1.3	1.1	-4.2	1.7
Iran	6398	1.6	10429	5.0	1.1	1.6	0.3
Iraq	1480	0.8	1200	0.7	-1.0	-1.6	4.0
Saudi Arabia	326	4.8	1549	6.6	-1.4	29.0	-5.1
Syria	1675	2.3	3765	-0.1	5.2	-3.6	3.6
Turkey	9363	2.0	18393	2.6	1.3	-0.3	0.2
Yemen	103	1.5	150	6.0	9.8	-1.6	3.3
South Asia	35240	2.4	85021	2.1	3.5	1.9	1.0
Bangladesh	683	2.0	1356	3.5	7.9	17.3	1.2
India	25585	2.6	65713	2.3	4.3	1.6	1.0
Myanmar	98	0.9	85	14.5	-4.0	4.9	-1.1
Nepal	648	1.6	1009	-1.1	8.8	4.2	2.5
Pakistan	8218	2.1	16853	1.7	1.1	2.0	1.1
East Asia	29921	3.8	112378	-0.1	1.3	0.3	0.1
China**	29510	3.8	112024	-0.3	1.4	0.2	0.1
Mongolia	328	0.7	237	24.7	-0.7	2.9	-3.4
North Korea	80	1.4	108	8.7	-6.3	0.0	-0.8
Mexico, Central America, and Caribbean	850	4.2	3525	1.0	0.0	6.4	-3.0
Mexico	837	4.2	3500	1.1	-0.2	7.0	-2.9
Andean Region, South America	309	1.1	341	-0.2	-2.7	-0.9	1.4
Bolivia	140	0.9	122	6.5	2.5	0.8	3.9
Peru	109	1.2	132	-0.5	-1.9	-3.3	0.8
Southern Cone, South America	8146	2.2	18160	0.3	2.1	1.1	-1.9
Argentina	5893	2.3	13386	1.1	-1.3	5.2	1.2
Brazil	1440	1.7	2445	-1.3	13.9	-6.0	-9.4
Chile	392	3.7	1429	-0.1	-1.8	-4.6	-4.3
Paraguay	206	1.9	384	12.7	3.5	16.8	4.6
Uruguay	215	2.4	516	-3.8	1.1	-3.3	0.9

* Data for 1993-97 (former Ethiopia).

** Data for China include figures for Hong Kong.

n.a. not available.

Growth of wheat yield (%/yr)				Growth of wheat production (%/yr)				Wheat area as percent of total cereal area (average) 1995-97 (%)
1951-66	1966-77	1977-85	1985-97 *	1951-66	1966-77	1977-85	1985-97 *	
0.1	4.1	0.7	2.6	2.2	5.1	1.0	1.5	8
2.0	3.3	1.5	-2.4	3.0	-2.5	5.5	7.7	12
1.2	1.1	1.9	0.2	0.3	0.0	1.5	1.6	9
-1.9	5.2	0.4	4.0	1.1	8.6	1.3	-0.9	24
-0.3	-0.1	5.2	2.0	8.0	13.4	-12.7	14.6	4
n.a.	8.0	1.2	-3.0	n.a.	35.6	14.7	9.5	2
7.1	4.4	4.5	-3.1	10.5	24.3	-2.9	-2.2	2
0.0	1.2	4.4	2.7	0.0	2.1	3.2	4.0	52
-0.9	0.3	4.4	2.1	-0.7	1.8	1.1	0.9	65
2.3	3.4	1.9	2.9	0.5	3.5	0.8	9.6	39
1.8	0.9	4.6	-3.3	2.5	0.7	5.0	-1.6	51
4.4	0.7	5.7	2.2	2.9	3.5	5.4	3.3	68
0.2	2.8	1.2	1.1	2.8	4.1	1.1	1.8	64
-0.1	1.7	0.7	0.8	1.2	2.8	-3.5	2.5	77
-1.3	2.2	0.3	4.1	3.8	3.3	1.9	4.4	72
1.5	0.5	3.7	-1.6	2.2	-0.5	2.1	2.4	48
1.3	-0.4	9.7	1.5	7.9	-1.8	38.7	-3.6	52
1.8	2.8	3.8	4.9	1.7	8.1	0.2	8.5	49
0.4	3.5	0.4	-0.1	3.0	4.8	0.1	0.1	67
0.5	-0.8	-1.9	1.0	6.5	9.0	-3.6	4.3	14
1.1	4.3	3.4	2.5	3.2	7.8	5.4	3.5	26
0.9	6.0	3.4	0.2	4.3	13.9	20.7	1.4	6
1.4	4.0	3.9	2.7	3.7	8.3	5.5	3.7	25
4.4	2.6	10.2	-6.4	18.9	-1.3	15.1	-7.4	2
2.1	-0.7	2.4	2.1	1.1	8.2	6.6	4.6	20
0.5	5.1	1.8	1.9	2.2	6.2	3.8	2.9	67
0.9	4.4	8.3	2.5	0.7	5.7	8.6	2.5	32
0.9	4.4	8.4	2.5	0.6	5.8	8.6	2.6	32
2.8	5.0	9.2	-6.7	27.5	4.3	12.1	-10.1	99
-7.8	8.4	2.1	-1.2	0.9	2.1	2.1	-2.0	6
7.3	3.8	3.0	0.3	8.3	3.8	9.5	-2.8	6
7.3	3.9	2.6	0.2	8.4	3.8	9.6	-2.7	8
0.7	-0.1	2.2	0.1	0.5	-2.8	1.3	1.5	6
0.1	3.1	1.7	1.6	6.5	5.5	2.4	5.5	19
0.1	0.6	0.8	-0.3	-0.5	-1.3	-2.6	0.5	12
1.7	0.8	5.7	2.5	1.9	2.8	6.8	0.6	26
1.8	3.1	3.4	2.7	2.9	1.8	8.6	3.9	58
-0.4	-1.2	7.9	0.3	-1.7	12.7	1.8	-9.1	7
1.9	-1.2	2.4	3.2	1.9	-3.0	-2.2	-1.1	62
1.4	-0.7	1.6	2.2	14.1	2.8	18.4	6.8	35
0.2	0.1	9.3	4.5	-3.6	1.3	6.0	5.4	35

Production statistics (cont'd.)

	Average wheat area, yield, and production, 1995-97			Growth of wheat area (%/yr)			
REGION / COUNTRY	Harvested area (000 ha)	Yield (t/ha)	Production (000 t)	1951-66	1966-77	1977-85	1985-97 *
Eastern Europe and former Soviet Union	57159	1.8	100204	2.4	-1.2	-2.5	-0.4
Albania	134	2.7	355	1.0	4.0	-0.7	-4.0
Azerbaijan	468	1.6	741	n.a.	n.a.	n.a.	1.8
Bulgaria	1117	2.6	2931	-1.7	-2.1	2.7	0.4
Croatia	212	3.9	817	n.a.	n.a.	n.a.	2.9
Czech Republic	818	4.6	3730	n.a.	n.a.	n.a.	1.0
Estonia	45	2.1	97	n.a.	n.a.	n.a.	0.6
Hungary	1183	3.3	3928	-2.1	1.0	1.0	-1.7
Kazakhstan	12104	0.6	7708	n.a.	n.a.	n.a.	-3.1
Kyrgyzstan	438	2.4	1039	n.a.	n.a.	n.a.	12.7
Latvia	137	2.4	332	n.a.	n.a.	n.a.	3.3
Lithuania	328	2.8	900	n.a.	n.a.	n.a.	3.3
Macedonia	121	2.6	315	n.a.	n.a.	n.a.	0.6
Moldova Republic	395	2.9	1159	n.a.	n.a.	n.a.	7.0
Poland	2481	3.4	8479	0.4	0.6	-0.4	2.2
Romania	2213	2.7	5989	0.7	-2.4	0.6	-1.0
Russian Federation	25224	1.4	36431	n.a.	n.a.	n.a.	1.6
Slovakia	421	4.4	1846	n.a.	n.a.	n.a.	0.1
Slovenia	35	4.1	144	n.a.	n.a.	n.a.	-5.7
Turkmenistan	506	1.1	573	n.a.	n.a.	n.a.	21.6
Ukraine	5960	2.7	16075	n.a.	n.a.	n.a.	1.2
Uzbekistan	1317	2.1	2721	n.a.	n.a.	n.a.	18.1
Yugoslavia, Fed. Rep. of	749	3.3	2459	n.a.	n.a.	n.a.	-1.4
Western Europe, Japan, and other high-income countries	64474	3.2	204835	-0.1	0.6	1.8	-0.4
Australia	10192	1.9	19615	5.1	0.2	2.4	-0.7
Austria	254	5.1	1298	2.5	-1.1	1.9	-2.5
Belgium-Luxembourg	216	7.9	1700	1.0	-1.2	0.0	0.9
Canada	11601	2.3	26337	1.1	-1.0	4.2	-1.9
Denmark	660	7.2	4734	4.2	2.3	15.1	6.5
Finland	112	3.9	434	5.2	-2.4	4.7	-3.8
France	4965	6.8	33559	0.1	0.4	2.7	0.1
Germany	2634	7.2	18837	1.5	2.1	0.2	0.8
Greece	862	2.4	2063	1.5	-2.0	-1.0	-0.3
Ireland	83	8.3	693	-4.3	-4.7	6.2	2.2
Italy	2419	3.1	7564	-0.8	-2.9	0.1	-2.7
Netherlands	138	8.3	1141	5.1	-2.3	1.0	1.0
New Zealand	51	5.5	281	5.6	-2.0	-4.4	-3.9
Norway	61	4.5	278	-13.0	20.8	7.7	4.2
Spain	2063	2.2	4608	-0.2	-4.5	-2.7	-0.6
Sweden	311	6.0	1880	-3.4	4.9	-0.5	0.3
Switzerland	100	6.3	635	0.8	-2.0	1.1	0.4
United Kingdom	1957	7.7	15143	0.2	2.5	6.9	-0.2
United States	25286	2.5	62974	-1.9	3.1	0.7	0.4
Regional aggregates							
Developing countries	104865	2.6	274193	1.1	1.9	0.8	0.4
Eastern Europe and former Soviet Union	57159	1.8	100204	2.4	-1.2	-2.5	-0.4
Western Europe, Japan, and other high-income countries	64474	3.2	204835	-0.1	0.6	1.8	-0.4
World**	226498	2.6	579232	1.2	0.5	0.1	-0.1

* Data for 1993-97 (former Czechoslovakia) and 1992-97 (former Soviet Union and former Yugoslavia).

** The world aggregates are not exactly equal to the FAO estimates because the method of aggregation may have differed.

n.a. not available.

Growth of wheat yield (%/yr)				Growth of wheat production (%/yr)				Wheat area as percent of total cereal area (average) 1995-97 (%)
1951-66	1966-77	1977-85	1985-97 *	1951-66	1966-77	1977-85	1985-97 *	
1.5	1.8	-0.2	-1.2	3.9	0.6	-2.8	-1.6	48
-0.2	6.1	3.8	-1.8	0.8	10.1	3.1	-5.8	58
n.a.	n.a.	n.a.	-3.5	n.a.	n.a.	n.a.	-1.6	75
3.1	3.3	-1.0	-3.8	1.4	1.3	1.7	-3.4	57
n.a.	n.a.	n.a.	-0.7	n.a.	n.a.	n.a.	2.3	34
n.a.	n.a.	n.a.	1.0	n.a.	n.a.	n.a.	2.0	51
n.a.	n.a.	n.a.	3.1	n.a.	n.a.	n.a.	3.6	15
2.7	5.3	3.2	-4.4	0.6	6.4	4.2	-6.0	42
n.a.	n.a.	n.a.	-11.6	n.a.	n.a.	n.a.	-14.7	70
n.a.	n.a.	n.a.	-0.8	n.a.	n.a.	n.a.	11.9	71
n.a.	n.a.	n.a.	1.5	n.a.	n.a.	n.a.	4.7	31
n.a.	n.a.	n.a.	1.9	n.a.	n.a.	n.a.	5.2	30
n.a.	n.a.	n.a.	0.1	n.a.	n.a.	n.a.	0.7	53
n.a.	n.a.	n.a.	-4.5	n.a.	n.a.	n.a.	2.5	43
3.8	3.3	2.5	-0.9	4.2	3.9	2.1	1.2	28
2.9	4.6	-0.4	-1.1	3.5	2.2	0.2	-2.2	36
n.a.	n.a.	n.a.	-4.3	n.a.	n.a.	n.a.	-2.7	48
n.a.	n.a.	n.a.	1.8	n.a.	n.a.	n.a.	2.0	50
n.a.	n.a.	n.a.	-0.1	n.a.	n.a.	n.a.	-5.8	35
n.a.	n.a.	n.a.	-16.4	n.a.	n.a.	n.a.	5.2	78
n.a.	n.a.	n.a.	-5.7	n.a.	n.a.	n.a.	-4.5	47
n.a.	n.a.	n.a.	9.8	n.a.	n.a.	n.a.	27.9	74
n.a.	n.a.	n.a.	-0.2	n.a.	n.a.	n.a.	-1.6	32
2.2	1.6	2.7	1.6	2.1	2.2	4.5	1.2	47
1.0	0.1	2.0	2.4	6.2	0.2	4.4	1.7	65
2.3	2.4	3.6	0.7	4.9	1.3	5.4	-1.8	31
1.3	2.5	4.6	2.2	2.3	1.3	4.6	3.1	69
0.3	1.7	-0.9	2.3	1.4	0.7	3.3	0.4	60
1.0	1.2	3.7	1.4	5.2	3.6	18.8	7.9	44
1.3	3.3	5.5	3.3	6.5	0.9	10.1	-0.5	11
3.4	2.6	3.8	1.6	3.5	3.0	6.5	1.6	57
1.4	1.6	3.4	1.9	2.9	3.7	3.6	2.6	39
2.8	3.1	-0.1	-0.3	4.3	1.1	-1.1	-0.6	66
2.1	1.4	4.8	2.1	-2.2	-3.3	11.0	4.4	29
1.8	1.0	2.3	1.4	1.0	-1.9	2.4	-1.2	57
1.3	2.2	3.4	1.4	6.4	-0.1	4.4	2.5	70
1.6	-0.1	3.2	3.2	7.1	-2.1	-1.1	-0.6	32
2.4	2.7	2.7	1.1	-10.6	23.4	10.5	5.3	18
1.1	2.4	5.3	-1.2	0.9	-2.1	2.6	-1.8	30
4.3	2.4	3.4	1.4	0.9	7.3	2.9	1.7	26
1.4	1.3	4.7	1.4	2.2	-0.7	5.8	1.8	51
2.8	1.6	4.4	1.8	3.0	4.1	11.3	1.7	58
3.3	1.1	3.0	0.5	1.4	4.2	3.7	0.9	40
1.0	3.4	5.1	2.2	2.0	5.3	5.9	2.5	23
1.5	1.8	-0.2	-1.2	3.9	0.6	-2.8	-1.6	48
2.2	1.6	2.7	1.6	2.1	2.2	4.5	1.2	47
1.5	2.1	3.0	1.3	2.6	2.6	3.1	1.2	32

Consumption statistics

	Average net wheat imports, 1995-97		Wheat consumption		Average percent wheat use	
REGION / COUNTRY	Total (000 t)	Per capita (kg/yr)	Average per capita, 1994-96 (kg/yr)	Growth rate per capita, 1987-96 (%/yr) *	Human consumption 1994-96 (%)	Animal feed 1994-96 (%)
Eastern and Southern Africa	2619	8	29	1.3	93	1
Angola	46	4	23	6.5	99	++
Eritrea	119	36	63	-2.6	95	++
Ethiopia	331	6	39	-1.4	91	++
Kenya	345	12	22	3.0	96	++
Mauritius	110	98	95	2.8	94	++
Mozambique	169	10	13	3.6	99	++
Somalia	10	1	6	-15.7	97	++
South Africa	837	20	69	-0.5	93	2
Sudan	216	8	44	2.6	95	++
Tanzania	84	3	5	-2.6	95	++
Zambia	30	4	11	1.2	97	++
Zimbabwe	108	9	28	-1.7	94	++
Western and Central Africa	1918	7	9	0.8	96	1
Cameroon	43	3	12	-11.5	97	++
Congo, Dem. Rep. of	142	3	5	-5.1	96	++
Côte d'Ivoire	233	17	17	-3.0	98	++
Ghana	140	8	8	-4.6	98	++
Guinea	n.a.	n.a.	14	-3.9	98	++
Mauritania	72	31	74	-0.1	97	++
Nigeria	766	7	7	13.5	94	2
Senegal	195	23	25	1.7	98	++
North Africa	12847	96	205	0.5	83	5
Algeria	2995	104	227	0.9	91	1
Egypt	5993	95	180	-0.1	81	8
Libya	340	61	262	1.6	63	21
Morocco	2280	84	219	1.1	84	3
Tunisia	1239	135	234	-0.2	86	1
West Asia	8687	37	210	-1.1	78	4
Afghanistan	120	6	131	-2.6	92	++
Iran	4330	62	200	0.6	87	6
Iraq	918	45	103	-12.1	87	++
Jordan	453	104	151	-0.4	94	++
Lebanon	386	125	167	0.4	74	5
Saudi Arabia	-198	-11	127	-1.2	95	++
Syria	-407	-28	272	1.8	79	7
Turkey	1899	31	320	-0.4	63	5
Yemen	967	62	126	1.6	98	++
South Asia	4753	4	67	0.9	88	1
Bangladesh	1078	9	22	-3.3	94	++
India	366	<1	67	1.0	87	1
Myanmar	5	<1	3	-3.7	93	++
Nepal	1	<1	44	0.5	79	3
Pakistan	2361	17	128	0.7	90	2
Sri Lanka	926	51	52	1.7	98	++

* Data for 1993-97 (former Ethiopia).
++ Not applicable.
n.a. not available.

Consumption statistics (cont'd.)

	Average net wheat imports, 1995-97		Wheat consumption		Average percent wheat use	
REGION / COUNTRY	Total (000 t)	Per capita (kg/yr)	Average per capita, 1994-96 (kg/yr)	Growth rate per capita, 1987-96 (%/yr) *	Human consumption 1994-96 (%)	Animal feed 1994-96 (%)
Southeast Asia and Pacific	7706	17	18	7.5	95	3
Indonesia	3927	20	20	10.0	98	++
Malaysia	1092	53	43	1.7	68	23
Papua New Guinea	108	24	29	10.7	99	++
Philippines	1801	26	26	4.5	100	++
Thailand	537	9	11	11.3	99	++
Viet Nam	131	2	5	5.2	99	++
East Asia	10950	8	93	0.3	86	4
China**	8247	7	94	0.4	86	3
Mongolia	0	0	173	-8.5	68	9
North Korea	73	3	28	-0.8	92	2
South Korea***	2630	58	74	-1.3	66	33
Mexico, Central America, and Caribbean	3610	23	51	-1.5	82	12
Costa Rica	185	53	51	-0.1	96	++
Cuba	714	65	83	-7.5	73	20
Dominican Republic	262	33	34	0.3	98	++
El Salvador	168	29	39	7.4	99	++
Guatemala	288	26	29	3.1	99	++
Haiti	9	1	32	2.4	95	++
Honduras	138	24	30	3.4	90	10
Jamaica	58	23	51	-6.6	98	++
Mexico	1356	15	54	-0.9	78	15
Nicaragua	86	20	24	-0.6	98	++
Panama	97	36	43	5.1	97	++
Trinidad and Tobago	141	109	77	-3.7	95	++
Andean Region, South America	3670	36	40	-1.0	97	0
Bolivia	181	24	59	1.1	90	++
Colombia	999	27	29	2.8	98	++
Ecuador	383	33	28	-6.7	98	0
Peru	1052	44	48	-1.3	97	++
Venezuela	989	44	46	-2.9	97	0
Southern Cone, South America	193	1	75	0.1	85	6
Argentina	-6395	-182	139	-1.1	84	4
Brazil	6216	39	54	0.9	90	4
Chile	552	38	136	-1.4	87	7
Paraguay	-93	-19	81	4.2	26	59
Uruguay	-87	-27	143	3.9	62	26
Eastern Europe and former Soviet Union	1164	3	262	-4.0	51	29
Albania	113	33	215	0.7	57	16
Armenia	232	64	158	-2.9	91	2
Azerbaijan	114	15	177	-4.4	91	1
Belarus	634	61	146	2.6	43	37
Bosnia Herzegovina	84	23	127	5.5	90	3
Bulgaria	-55	-7	348	-6.9	43	37
Croatia	-22	-5	150	-0.3	57	31
Czech Republic	-312	-30	350	14.8	30	59
Estonia	23	15	103	2.6	70	21

* Data for 1993-97 (former Czechoslovakia), 1992-97 (former Soviet Union and former Yugoslavia).

** Data for China include figures for Hong Kong.

*** South Korea is a high-income country but is included here for greater geographical consistency with previous *Wheat Facts and Trends*.

++ Not applicable.

Consumption statistics (cont'd.)

	Average net wheat imports, (1995-97)		Wheat consumption		Average percent wheat used	
REGION / COUNTRY	Total (000 t)	Per capita (kg/yr)	Average per capita, 1994-96 (kg/yr)	Growth rate per capita, 1987-96 (%/yr) *	Human consumption 1994-96 (%)	Animal feed 1994-96 (%)
Eastern Europe and former Soviet Union (cont'd.)						
Georgia	293	54	146	-2.6	96	++
Hungary	-1337	-133	283	-7.2	39	42
Kazakhstan	-2392	-142	464	-3.2	46	15
Kyrgyzstan	103	23	250	-6.5	71	14
Latvia	57	23	126	3.4	72	10
Lithuania	-3	-1	230	1.5	56	27
Macedonia	93	43	191	-4.1	55	4
Moldova Republic	-25	-6	228	-12.8	57	23
Poland	1219	32	229	-2.0	48	39
Romania	-781	-34	224	-4.6	62	13
Russian Federation	1815	12	273	-6.5	47	32
Slovakia	-171	-32	345	-3.6	31	59
Slovenia	104	54	144	-8.9	53	21
Tajikistan	326	55	192	-1.0	98	++
Turkmenistan	205	49	289	-11.7	57	32
Ukraine	-594	-12	310	-8.2	43	35
Uzbekistan	1492	64	182	1.7	96	++
Yugoslavia, Fed. Rep. of	-72	-5	234	-7.7	45	17
Western Europe, Japan, and other high-income countries	-58005	-68	155	1.3	53	35
Australia	-13921	-771	199	-0.7	37	20
Austria	-265	-33	131	1.2	49	43
Belgium-Luxembourg	2216	210	223	4.0	41	38
Canada	-17388	-586	269	1.9	31	54
Denmark	-1038	-198	623	8.0	12	81
Finland	157	31	88	-1.6	60	20
France	-14802	-254	302	4.1	32	57
Germany	-2778	-34	176	0.4	36	53
Greece	366	35	168	-1.1	82	4
Ireland	225	63	265	2.4	39	52
Israel	829	147	221	3.3	60	22
Italy	5975	104	183	-0.6	80	13
Japan	6069	48	53	0.6	87	7
Netherlands	2238	144	156	4.6	36	50
New Zealand	207	57	119	1.8	62	18
Norway	188	43	119	0.3	78	19
Portugal	1073	109	129	1.6	75	14
Spain	2284	58	140	-0.2	65	22
Sweden	-287	-33	178	5.6	40	48
Switzerland	242	33	130	0.6	70	24
United Kingdom	-2446	-42	201	-0.1	43	45
United States	-28096	-104	125	1.2	70	22
Regional aggregates						
Developing countries	56953	13	74	0.3	85	4
Eastern Europe and former Soviet Union	1164	3	262	-4.0	51	29
Western Europe, Japan, and other high-income countries	-58005	-68	155	1.3	53	35
World**	—	—	100	-0.7	71	16

* Data for 1993-97 (former Czechoslovakia), 1992-97 (former Soviet Union and former Yugoslavia).

** The world aggregates are not exactly equal to the FAO estimates because the method of aggregation may have differed.

++ Not applicable.

CIMMYT wheat experimental and national average yield, 1995-97 (t/ha)

COUNTRY/REGION *	Experimental wheat yield	National average wheat yield
Kenya	2.9 [1, 5, 7]	1.9
Madagascar	6.8 [1]	2.0
Malawi	1.5	0.7
South Africa	7.3	1.7
Sudan	3.0 [2, 3]	1.9
Swaziland	9.9 [4]	1.5
Tanzania	2.2	1.9
Zimbabwe	6.6	4.1
Eastern and Southern Africa	**5.0**	**2.0**
Algeria	2.5	1.1
Egypt	6.0	5.6
Lybia	9.4 [1]	1.2
Morocco	4.1	1.2
Tunisia	3.1	1.4
North Africa	**5.0**	**2.1**
Afghanistan	4.0	1.3
Iran	5.0	1.6
Jordan	2.3 [1]	1.4
Saudi Arabia	6.4	4.8
Syria	3.7 [2, 3]	2.4
Turkey	8.7	2.0
Yemen Democratic Rep.	1.5 [6]	1.2
West Asia	**4.5**	**2.1**
Bangladesh	4.4	2.0
India	4.4	2.6
Myanmar	2.4	0.9
Nepal	1.8	1.6
Pakistan	3.3	2.1
South Asia	**3.3**	**1.8**
Thailand	2.2	0.7
Vietnam	2.3	
Southeast Asia and the Pacific	**2.2**	**0.7**
China	6.0	3.8
South Korea	3.6 [7]	4.0
Taiwan	1.4 [1]	
East Asia	**4.8**	**3.9**

COUNTRY/REGION *	Experimental wheat yield	National average wheat yield
Guatemala	5.3	2.1
Mexico	5.3 [1, 5]	4.1
Mexico,Central America, and the Caribbean	**5.3**	**3.1**
Bolivia	2.9	0.9
Colombia	2.4 [1, 3]	1.9
Ecuador	2.5	0.7
Peru	5.4	1.2
Andean Region	**3.3**	**1.2**
Argentina	3.0	2.3
Brazil	3.6	1.7
Chile	7.2	3.6
Paraguay	3.3	1.9
Uruguay	3.2	2.4
South America	**4.1**	**2.4**
Bulgaria	5.1 [3]	2.9
Czech Rep.	7.3	4.6
Poland	5.3	3.4
Romania	2.4 [5]	1.8
Ukraine	3.5	2.7
Yugoslavia	3.4 [1]	4.3
Eastern Europe and former Soviet Union	**4.5**	**3.3**
Canada	4.0	2.3
France	7.1	6.8
Greece	3.4 [1, 4]	2.3
Italy	5.6	3.1
Japan	3.5 [5]	3.0
New Zealand	6.1	5.5
Portugal	2.5	1.3
Qatar	6.2 [2]	2.3
Spain	4.6	2.2
United Kingdom	7.4 [2]	6.8
Western Europe, North America, and other high-income countries	**4.8**	**3.6**
Total	**4.4**	**2.5**

* Regional aggregates include only countries that have been reported.

Notes: [1] 1990, [2] 1992, [3] 1993, [4] 1995, [5] 1996, [6] 1997, [7] 1998

Wheat area by type of wheat (%)

COUNTRY/REGION*	Wheat area by type of wheat, 1997 (%) Spring bread	Spring durum	Winter bread	Winter durum	Wheat area under semidwarf wheat varieties, 1997 (%)
Ethiopia	60	40	0	0	51
Kenya	100	0	0	0	100
South Africa	55	0	45	0	70
Sudan	100	0	0	0	80
Tanzania	100	0	0	0	98
Zambia	100	0	0	0	100
Zimbabwe	100	0	0	0	100
Eastern and Southern Africa	**65**	**16**	**19**	**0**	**66**
Nigeria	100	0	0	0	99
Western and Central Africa	**100**	**0**	**0**	**0**	**99**
Algeria	44	56	0	0	71
Egypt	94	6	0	0	98
Morocco	57	43	0	0	95
Tunisia	15	85	0	0	89
North Africa	**54**	**46**	**0**	**0**	**88**
Afghanistan	0	0	100	0	31
Iran	48	0	52	0	59
Jordan	21	79	0	0	57
Lebanon	0	100	0	0	83
Syria	39	61	0	0	95
Turkey	19	18	50	13	58
Yemen	100	0	0	0	43
West Asia	**30**	**14**	**51**	**6**	**59**
Bangladesh	100	0	0	0	100
India	100	0	0	0	92
Nepal	100	0	0	0	92
Pakistan	100	0	0	0	94
South Asia	**100**	**0**	**0**	**0**	**92**
China	44	0	56	0	79
East Asia	**44**	**0**	**56**	**0**	**79**
Guatemala	100	0	0	0	100
Mexico	53	47	0	0	99
Mexico, Central America, and the Caribbean	**54**	**46**	**0**	**0**	**99**
Bolivia	90	10	0	0	80
Colombia	100	0	0	0	99
Ecuador	100	0	0	0	100
Peru	83	17	0	0	83
Andean Region	**90**	**10**	**0**	**0**	**85**
Argentina	100	0	0	0	98
Brazil	100	0	0	0	53
Chile	41	14	45	0	95
Paraguay	100	0	0	0	100
Uruguay	76	0	24	0	85
South America	**97**	**1**	**3**	**0**	**89**
TOTAL	**66**	**6**	**26**	**1**	**81**

* Regional aggregates include only countries that have been reported.

Prices and input use for wheat

REGION / COUNTRY	Farm prices of wheat, 1998-99 (US$/t)		Consumer price of wheat flour, 1998-99 (US$/t)	Ratio of farm-level fertilizer price to wheat price 1998-99			Fertilized area, 1998 (%)	Fertilizer applied per hectare of wheat harvested, 1998 (kg nutrients/ha)	Farm wage in kg of wheat per day, 1998
	Bread	Durum		Nitrogen	Phosphorus	Potassium			
Eastern and Southern Africa									
Ethiopia	173	173	443	2.2	++	++	84	67	5
Sudan	194	++	400	3.6	++	++	100	190	4
Tanzania	209	++	468	2.6	++	++	1	n.a.	10
Zimbabwe	316	++	516	n.a.	++	++	100	300	3
North Africa									
Algeria	262	292	462	3.9	2.9	++	8	500	57
West Asia									
Saudi Arabia	400	400	545	4.0	2.0	7.5	n.a.	n.a.	n.a.
Turkey	159	208	524	3.3	4.2	7.4	98	198	84
South Asia									
Bangladesh	179	++	333	1.8			100	125	6
India	131	148	180	4.4	3.4	2.1	94	156	10
Nepal	139	++	241	6.8	4.6	++	80	100	6
East Asia									
China	133	224	234	3.5	2.7	2.1	97	246	8
Mongolia	78	88	299	3.3	3.0	2.3	30	35	19
Mexico, Central America, and the Caribbean									
Mexico	137	147	263	2.7	3.5	++	80	240	38
Andean Region									
Bolivia	158	++	344	11.1	6.6	4.9	11	71	31
Colombia	226	++	566	8.7	4.8	17.8	30	200	34
Ecuador	317	++	514	2.5	2.9	1.8	40	160	27
South America									
Argentina	115	++	390	13.0	7.5		90	66	108
Brazil	94	191	244	31.3	10.8	14.7	92	162	73
Chile	194	194	536	2.8	3.2	2.4	85	140	48
Uruguay	105	++	636	9.3	5.6	++	100	100	155
Eastern Europe and former Soviet Union									
Bulgaria	70	80	140	5.2	++	++	70	100	78
Western Europe, North America, and other high-income countries									
Canada	115	161	665	5.9	5.0	++	70	50	499
Spain	152	163	227	5.1	5.5	6.0	95	400	245
Finland	136	++	399	6.0	16.4	++	100	600	55
France	112	++	573	15.2	9.7	9.7	100	380	629
Germany	115	184	686	4.0	10.4	6.0	100	315	668
Greece	166	163	1000	4.3	12.2	++	95	14	184
Ireland	70	++	365	4.2	++	++	100	265	401
Italy	161	158	421	5.9	++	++	94	290	519
Netherlands	135	++	1779	5.4	9.0	7.1	100	180	692
Portugal	147	164	352	11.6	6.6	8.5	100	230	180
Switzerland	473	++	1190	1.5	++	++	95	324	115
United Kingdom	148	++	1066	22.9	++	++	98	190	444
United States	106	117	1326	7.2	++	++	95	140	528

++ not applicable.
n.a. not available.

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Appendix A

Regions of the World

Developing Countries

EASTERN AND SOUTHERN AFRICA

- Angola
- Botswana
- Burundi
- Comoros
- Djibouti
- Eritrea
- Ethiopia
- Kenya
- Lesotho
- Madagascar
- Malawi
- Mauritius
- Mozambique
- Namibia
- Rwanda
- Seychelles
- Somalia
- South Africa
- Sudan
- Swaziland
- Tanzania
- Uganda
- Zambia
- Zimbabwe

WESTERN AND CENTRAL AFRICA

- Benin
- Burkina Faso
- Cameroon
- Cape Verde
- Central Africa Republic
- Chad
- Congo, Democratic Republic of
- Congo, Republic of
- Côte d'Ivoire
- Equatorial Guinea
- Gambia
- Ghana
- Guinea
- Guinea-Bissau
- Liberia
- Mali
- Mauritania
- Niger
- Nigeria
- Sao Tome and Principe
- Senegal
- Sierra Leone
- Saint Helena
- Togo

NORTH AFRICA

- Algeria
- Egypt
- Libya
- Morocco
- Tunisia

WEST ASIA

- Afghanistan
- Bahrain
- Iran
- Iraq
- Jordan
- Lebanon
- Oman
- Saudi Arabia
- Syria
- Turkey
- Yemen

SOUTH ASIA

- Bangladesh
- Bhutan
- India
- Maldives
- Myanmar
- Nepal
- Pakistan
- Sri Lanka

SOUTHEAST ASIA AND THE PACIFIC

- American Samoa
- Cook Islands
- East Timor
- Fiji
- Indonesia
- Kiribati
- Laos
- Malaysia
- Nauru
- Niue Island
- Norfolk Island
- Papua New Guinea
- Philippines
- Samoa
- Solomon Islands
- Thailand
- Tokelau
- Tonga
- Tuvalu
- Vanuatu
- Vietnam
- Wallis and Futuna Island

EAST ASIA

- China
- Mongolia
- North Korea
- South Korea

MEXICO, CENTRAL AMERICA, AND THE CARIBBEAN

- Antigua and Barbuda
- Barbados
- Belize
- Costa Rica
- Cuba
- Dominica
- Dominican Republic
- El Salvador
- Grenada
- Guadeloupe
- Guatemala
- Haiti
- Honduras
- Jamaica
- Mexico
- Montserrat
- Netherlands Antilles
- Nicaragua
- Panama
- Saint Kitts and Nevis
- Saint Lucia
- Saint Pierre Miquelon
- Saint Vincent
- Grenadines
- Trinidad and Tobago

ANDEAN REGION, SOUTH AMERICA

- Bolivia
- Colombia
- Ecuador
- Guyana
- Peru
- Suriname
- Venezuela

SOUTHERN CONE, SOUTH AMERICA

- Argentina
- Brazil
- Chile
- Falkland Islands
- Paraguay
- Uruguay

Eastern Europe and Former Soviet Union

- Albania
- Armenia
- Azerbaijan
- Belarus
- Bosnia Herzegovina
- Bulgaria
- Croatia
- Czech Republic
- Estonia
- Georgia
- Hungary
- Kazakhstan
- Kyrgyzstan
- Latvia
- Lithuania
- Macedonia
- Moldova Republic
- Poland
- Romania
- Russian Federation
- Slovakia
- Slovenia
- Tajikistan
- Turkmenistan
- Ukraine
- Uzbekistan
- Yugoslavia, Fed. Rep. of

Western Europe, Japan, and Other High-Income Countries

- Australia
- Austria
- Belgium-Luxembourg
- Brunei Darussalam
- Canada
- Cyprus
- Denmark
- Faeroe Island
- Finland
- France
- Germany
- Greece
- Greenland
- Iceland
- Ireland
- Israel
- Italy
- Japan
- Kuwait
- Malta
- Netherlands
- New Zealand
- Norway
- Portugal
- Qatar
- Singapore
- Spain
- Sweden
- Switzerland
- United Arab Emirates
- United Kingdom
- United States

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