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Sources of Productivity Growth in Wheat: A Review of Recent Performance and Medium- to Long-Term Prospects

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Abstract

Sources of yield growth in wheat are investigated based on a stylized framework of technical change. Evidence suggests that the relative contribution of input intensification to yield growth has diminished in recent years and is likely to continue to decline in the future. One potential source of yield growth in wheat during the medium to long term is improved efficiency of input use, rather than input intensification, through sustainable wheat production practices rather than pure input increases. Other large gains could be made with continuous adoption of newer and better modern varieties based on advances in wheat breeding. Wide crossing and biotechnology could improve the stability of wheat yields in the intermediate term; their long-term impact on yield under optimal conditions is less certain. World wheat demand is likely to grow more slowly over the next 30 years than it did in the past 30 years. At the same time, a wider variety of technological options will need to be tapped over the next three decades to achieve the necessary gains in wheat yields. Research costs per unit of increased wheat production are likely to be somewhat higher. Nonetheless, continued investment in wheat research is necessary to achieve production levels consistent with constant or slowly declining real world wheat prices.

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Sources of Productivity Growth in Wheat: A Review of Recent Performance and Medium- to Long-Term Prospects

Roderick M. Rejesus, Paul W. Heisey, and Melinda Smale

Introduction

The objective of this paper is to examine the sources of output and productivity growth in wheat in recent decades, together with current patterns of technology development, and to draw implications for the coming decades. Total world wheat output must grow at a rate of 1.4–1.5% per year over the next 25 years to meet projected demand while slightly decreasing the real price of wheat. If world wheat output grows more slowly, the real price of wheat will rise. Demand in developing countries may grow at slightly more than 2% per year over the same period. Even with output growth of more than 2% per year, wheat imports in these countries will nearly double between 1990 and 2020 (Rosegrant, Agcaoili-Sombilla, and Perez 1995).

With the possible exception of the former Soviet Union (FSU), additional area sown to wheat will no longer contribute significantly to future wheat production increases. The medium- and long-term outlook for wheat production is highly dependent on systematic factors that affect wheat yields, such as the pattern of input use by farmers and potential advances in the technology of wheat production. These and other issues that may affect future productivity are investigated in this paper.

The first section briefly reviews worldwide yield increases in wheat during the past 40 years and summarizes recent forecasts of future yield increases. The second section presents a framework for examining sources of productivity growth within the context of a technical change cycle. Using this framework, the following three sections present empirical evidence on potential sources of yield growth, namely: yield growth from input intensification, yield growth from input efficiency, and long-term yield changes from new technologies. The empirical evidence is drawn primarily from the major wheat-producing areas of South Asia, Mexico, and the USA. Mexico is of interest because it is usually among the first countries in which new modern varieties (MVs)[1] and related technologies from the International Maize and Wheat Improvement Center (CIMMYT) are tested in farmers' fields. South Asia (India and Pakistan in particular) is important because this is the first area where MVs were widely diffused and, in the aggregate, it has the greatest area planted to wheat in the developing world. The USA, on the other hand, is the biggest producer among the high-income countries. Data from other major producing countries, including China, FSU nations, and Australia, are reported whenever available. A summary of the major issues discussed in this paper is presented in the concluding section.

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[1] The term "modern varieties" (MVs) used in this paper refers to semidwarf varieties of wheat that have a height of less than 100 cm under good growing conditions and carry one or more dwarfing genes, usually Rht1 and Rht2, although in some cases Rht8 and Rht9 are important. Improved plant characteristics such as yield potential or disease resistance are generally incorporated into these semidwarf varieties.

Historical Yield Increases and Future Projections

Yield increases have been the most important source of growth in world wheat production over the past four decades. The world experienced the highest rate of yield growth in wheat during the 1960s and 1970s. The growth rate in world yields in the past decade was, however, substantially lower than that of previous decades. In advanced Green Revolution areas, such as the Yaqui Valley of Mexico or the Indian Punjab, there is also evidence that yield growth in wheat at a more disaggregated level is slowing or leveling off (Sayre 1996; Murgai 1997). Yield growth during 1986–95 in developing countries was still higher than in other regions, despite a greater decrease from the growth rates of preceding decades (Table 1).

The periods of greatest contribution of yield growth to growth in wheat production vary between regions. Yield growth in the high-income economies increased sharply during the 1960s, but the rate of yield growth during the 1970s was almost the same as that of the preceding decade. Yield increases in developing countries have been higher than in high-income countries during the past 30 years. In the developing countries, there were consecutive large yield increases during the 1960s and the 1970s. By contrast, wheat yields in Eastern Europe and the former Soviet Union (FSU) grew only during 1966–75 and decreased considerably in subsequent decades.

Partially disaggregating figures from the developing countries indicates that the general pattern of relatively rapid yield increases in the 1960s and 1970s, followed by lower rates of yield growth in the last decade, holds for most of the major producing regions. Only in Latin America and sub-Saharan Africa is the pattern somewhat more variable. Yield growth has been particularly rapid in certain periods in China, India, and the rest of Asia, excluding West Asia (Table 2).

Based partially on the recent slowdown in cereal yields generally, some observers (e.g., Brown 1995) have suggested that most mainstream projections of future increases in cereal yields (such as those presented for wheat in Table 3) are based on "simple extrapolation" of steady growth in world cereals production. Comparing Table 3 with Tables 1 and 2 shows that this is not the case. Projected rates of increase in wheat

Table 1. Growth rates in wheat area, production, and yield, by periods (in %/yr)

Period	Area	Production	Yield
World			
1956–65	0.6	1.4	0.8
1966–75	0.2	2.3	2.1
1976–85	0.1	2.7	2.7
1986–95	-0.3	0.7	1.0
High-income countries			
1956–65	1.4	3.3	1.9
1966–75	-0.3	1.9	2.2
1976–85	1.4	4.0	2.6
1986–95	-0.6	0.9	1.5
Eastern Europe and FSU			
1956–65	0.6	-0.6	-1.2
1966–75	-1.4	-0.2	1.2
1976–85	-2.1	-2.5	-0.4
1986–95	-0.8	-2.6	-1.8
Developing countries			
1956–65	0.2	1.2	1.0
1966–75	2.0	5.5	3.5
1976–85	0.6	5.0	4.5
1986–95	0.3	2.1	1.8

Source: FAO Agrostat.

yields are generally expected to be lower during the next 20 to 30 years than even the reduced rates of 1986–95.[2,3] Comparing current versions of International Food Policy Research Institute (IFPRI) data (M. Agcaoili-Sombilla, personal communication) with published estimates (Rosegrant, Agcaoili-Sombilla, and Perez 1995) suggests that IFPRI has further revised downward projected rates of yield increase for wheat. In general, projected rates of yield increases for developing countries (roughly 1.4–2.0% per year) over the next 20 to 30 years are about double those for high-income countries or Eastern Europe and the FSU (0.7–1.0% per year). There is some question about whether the rates of yield increase in these high-income and transitional economies are constrained by demand or policy factors as much, if not more than, by technical factors (Alexandratos 1996; Folmer et al. 1995). Nonetheless, yields will have to increase close to those projected rates if future scenarios of continued, though smaller, declines in the real price of wheat together with increased per capita wheat consumption in developing countries are to materialize (Rosegrant, Agcaoili-Sombilla, and Perez 1995). The following pages present further analyses of past, present, and potential sources of yield growth in wheat.

Table 2. Regional growth rates in developing countries in wheat area, production, and yield, by periods (in %/yr)

Period	Area	Production	Yield
Asia[a] less China, India			
1956–65	2.4	3.3	0.9
1966–75	0.9	5.9	5.0
1976–85	3.0	5.2	2.2
1986–95	1.0	2.4	1.4
China			
1956–65	-1.1	-1.8	-0.7
1966–75	1.4	6.0	4.7
1976–85	0.3	7.6	7.3
1986–95	0.1	2.2	2.1
India			
1956–65	1.0	3.3	2.3
1966–75	4.7	9.3	4.6
1976–85	1.7	5.3	3.6
1986–95	1.0	3.6	2.6
West Asia/North Africa			
1956–65	0.9	1.6	0.7
1966–75	1.5	3.4	1.9
1976–85	-0.6	0.8	1.4
1986–95	1.5	2.5	1.1
Latin America			
1956–65	-0.8	2.7	3.5
1966–75	0.8	2.7	1.9
1976–85	0.0	4.6	4.6
1986–95	-4.3	-2.7	1.6
Sub-Saharan Africa[b]			
1956–65	1.5	4.3	2.8
1966–75	2.9	6.5	3.6
1976–85	0.6	0.5	-0.1
1986–95	-2.2	-0.3	1.9

Source: FAO Agrostat.

[a] Does not include West Asia, which is included in West Asia and North Africa.

[b] Includes South Africa.

Conceptual Framework

Byerlee (1992) has described a sequential process of technical change that is useful in analyzing the sources of productivity gains in wheat production. It consists of four phases, which may chronologically overlap among a cross-section of farmers. The cycle is not a deterministic model in which one phase inevitably follows the other. It is presented in a sequential manner solely for ease of exposition and presentation of empirical evidence.

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[2] A notable exception to this statement is the IFPRI projection for the West Asia/North Africa (WANA) region.

[3] The projections of wheat yield increases in Table 3 are also consistent with the overall projections for cereals made by Mitchell and Ingco (1993).

Table 3. Projected growth rates in wheat yield (in %/yr)

Region	Period	Growth Rate		Source
Industrialized countries[a]	1990–2020		1.0	Rosegrant, Agcaoili-Sombilla, and Perez (1995)
High-income countries	1993–2020		0.7	calculated from data provided by M. Agcaoili-Sombilla (pers. comm.)
Eastern Europe and FSU	1993–2020		1.0	calculated from data provided by M. Agcaoili-Sombilla (pers. comm.)
All developing countries[b]	1987–2000	"Optimistic"	2.3	CIMMYT (1989)
All developing countries[b]	1987–2000	"Realistic"	1.5	CIMMYT (1989)
Developing countries less China	1990–2010		1.6	Alexandratos (1995)
All developing countries	1990–2020		1.8	Rosegrant, Agcaoili-Sombilla, and Perez (1995)
All developing countries	1993–2020		1.4	calculated from data provided by M. Agcaoili-Sombilla (pers. comm.)
All developing countries	1990–2030		1.9	Crosson and Anderson (1992)
Asia[c] less China, India	1993–2020		1.4	calculated from data provided by M. Agcaoili-Sombilla (pers. comm.)
China	1993–2020		1.5	"
India	1993–2020		2.0	"
West Asia/North Africa	1993–2020		1.5	"
Latin America	1993–2020		1.2	"
Sub-Saharan Africa[d]	1993–2020		1.2	"

[a] Includes both high-income countries, and Eastern Europe/FSU.

[b] Excludes yield increases from managerial changes leading to greater efficiency.

[c] Does not include West Asia, which is included in West Asia and North Africa.

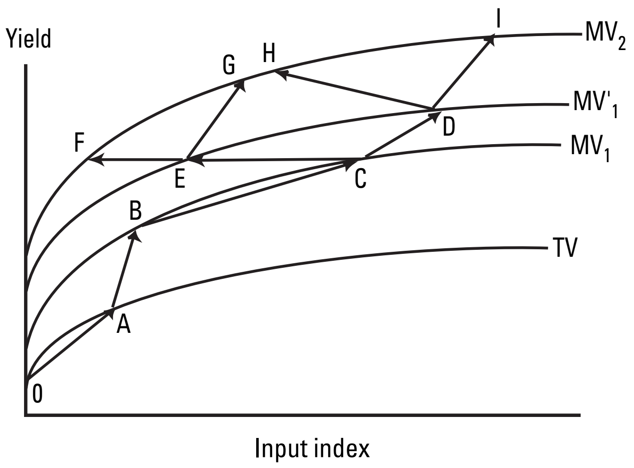
[d] Excludes South Africa.

In the *Pre-Green Revolution Phase,* gains in productivity per unit area are modest and area expansion is the major source of wheat production increases. In the *Green Revolution Phase,* modern varieties become available that enable a dramatic jump in productivity even with modest levels of purchased inputs and management practices. In the *First Post-Green Revolution Phase,* farmers move toward improving *allocative efficiency* by adjusting the use of purchased inputs toward their optimal levels—where the marginal value product is equated to the acquisition price. Historically, input use in this phase intensifies. In the *Second Post-Green Revolution Phase,* farmers achieve greater *technical efficiency* in using available purchased inputs through better use of non-purchased inputs such as information and management skills. Farmers' accumulated experience with a technology leads to a better understanding of the technical relationships between inputs and outputs, hence information and management skills substitute for greater input use.

Figure 1 depicts these phases in the conventional framework of a response function. Phase 1 can be depicted as a move from *0* to *A*, in which yield growth can be attributed to greater labor intensity or improvement of land quality through investments such as irrigation systems. During this phase, however, expansion of planted area for the traditional varieties (TVs) that have not been improved scientifically—not yield growth—is the major source of increased output. During the Green Revolution Phase, the introduction of scientifically bred MVs shifts the response function upwards (TV to MV_1), increasing crop response to inputs such as fertilizer and water and leading to a surge in production (*A* to *B*). The steeper slope of the new response function (MV_1) reflects the larger marginal effect on yield of input use. Adoption of modest levels of complementary inputs accompanies the adoption of MVs, but for various reasons, farmers may not exploit the full benefits of the new technology and may continue to operate well below the technological frontier, which is represented by MV'_1 .

During the First Post-Green Revolution Phase, farmers become familiar with the input-output price relationships associated with the new MVs, and they move along the technically inefficient production function to improve allocative efficiency—typically increasing their level of input use (*B* to *C*). However, optimally allocating inputs is often difficult due to the imperfect input-output price information available to farmers. Farmers adjust to the "optimal" input levels based on the price information available to them, which may not be the actual economic optima. Hence, allocating inputs to economically optimal levels is a continuous process, which often overlaps with other phases of the technical change cycle.

During the Second Post-Green Revolution Phase, farmers approach the new production frontier (MV'_1) by employing better technical information and crop management skills to further increase input-use efficiency. Since there is no inherent change in technology, the shift from MV_1 to MV'_1 does not change the slope of the yield response function. Farmers' experience with MVs, together with changes in supporting institutions and policies, may evolve to allow improved managerial and information skills to substitute for increased input use. Acquisition of new information on technical and input-output price relationships in this phase also implies a continuing adjustment in the allocation of purchased inputs and adjustments in the use of non-purchased inputs. Gains from productivity in this phase, however, result more from increased technical efficiency than from allocative efficiency. Depending on the institutional/policy environment and farmers' strategies, input use may expand



OA	Phase I	Intensification of "traditional" inputs (expansion of land area)
AB	Phase II	Land-saving technological breakthrough
BC	Phase III	Input intensification (allocative efficiency)
CD or CE	Phase IV	Input efficiency (technical efficiency)
MV'_1 to MV_2	Phase V	New scientific breakthrough

Figure 1. A simplified framework of technical change in wheat production.

Source: Modified from Byerlee (1992).

modestly (*C* to *D*) or decrease (*C* to *E*) (Figure 1). The move from *C* to *E* means that yield will remain the same, but input use will decrease; the move from *C* to *D* implies a modest increase in input use combined with a higher gain in yield. In either case, increases in total factor productivity (TFP) may be quite rapid in this phase.[4] Technical efficiency also contributes to sustaining the agricultural resource base because efficient farmers recognize that the resource base is critical for future productivity and hence, if economically possible, will not use resource-degrading practices.

To depict potential sources of long-term yield growth, another phase that may be termed the *Third Post-Green Revolution Phase* or the *New Scientific Breakthrough Phase* can be added to the process of technical change proposed by Byerlee (1992) (Figure 1). A previously untapped scientific or technological variable may push the production frontier farther and the slope steeper, so that yield response to inputs would be even higher (MV'_1 to MV_2). Depending on the nature of future technological breakthroughs and shifts in relative prices, the use of complementary inputs may also increase or decrease.

Available evidence on input use is summarized in the following section. This will allow us to draw some conjectures about which phase of technical change various wheat producing countries or regions are in at present. In summary, it can be said that countries or regions that have favorable natural environments for wheat production, adequate research, physical and market infrastructure, and relatively supportive policies tend to be further along the technical change sequence (Pingali and Heisey 1996). For the most part, they would be closest to the Second Post-Green Revolution Phase. Countries or regions that do not satisfy one or more of these conditions are likely to be earlier in the technical change sequence, or they may not fit neatly into this stylized scheme.

In terms of political, economic, and geographical regions, favorably endowed wheat producing regions in the developing world (irrigated or high rainfall areas without excessive heat stress) are probably in the Second Post-Green Revolution Phase. More marginal developing-country environments, where high-yielding varieties have begun to spread, might be between the Green Revolution and First Post-Green Revolution Phases; and even more marginal areas would be in the Pre-Green Revolution Phase. In industrialized Western nations, a long history of research and infrastructure development places many wheat producing regions in the Second Post-Green Revolution Phase, with some important qualifications. Less favorable (drier, short growing season) environments in these countries (parts of the USA, Canada, and Australia), for example, may not have experienced as rapid wheat yield growth as Post-Green Revolution areas in developing countries.[5] Eastern Europe and the FSU are the most difficult areas to characterize in terms of technical change and wheat production, because large economic discontinuities have led to infrastructural collapse in many cases. Additionally, relatively harsh growing conditions in the FSU also influence wheat production and technical change.

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[4] Total factor productivity relates an index of output to an index of all inputs used in production. Even so, it may omit the use of unmeasurable, unpriced inputs such as environmental services.

[5] As we shall see in the next section, parts of the US wheat area and most of the Canadian wheat area are not planted to semidwarf wheat, although they are sown to improved varieties resulting from scientific plant breeding programs.

Changes in Input Use

Semidwarf wheat varieties, fertilizers, and investment in irrigation are the inputs that have contributed most to the large yield increases observed during the past three decades—especially in developing countries. This section summarizes available data spanning the past 30 years on changes in the levels of use of these three inputs, as well as the use of pesticides and mechanization.

Modern Varieties[6]

The release and adoption of semidwarf varieties, which spawned the "Green Revolution" in developing countries, provided a major source of yield increases in the 1960s and 1970s (Dalrymple 1977, 1986; Byerlee and Moya 1993). The area planted to MVs has expanded steadily since 1966. In 1969/70, semidwarf wheat varieties occupied 12 million ha in developing countries, or about 21% of the wheat area in the developing world. By 1994, this area was more than 70 million ha, or more than 70% of the wheat area in the developing world (Table 4). Among the developing regions, the largest area sown to MVs is still found in South Asia (31.4 million ha or 91% of wheat area), although between 1970 and 1990, semidwarf wheat area expanded substantially in other major developing regions (Byerlee and Moya 1993).

Much wheat area in high-income countries, probably more than half, is also planted to semidwarf varieties. Varieties with CIMMYT ancestry are found on more than 20 million ha (Byerlee and Moya 1993). Particularly in high-income countries, however, there is no direct relationship between wheat varieties that are semidwarf and wheat varieties that have CIMMYT parentage. Most of the semidwarf material planted in Australia has some CIMMYT ancestry. In Canada, on the other hand, around one-third of the wheat area is planted to material with some CIMMYT ancestry, but very little area is sown to semidwarf varieties.[7] Under dry conditions, short stature may result in plants that are too short for machine harvesting. Long daylight hours and quality considerations also constrain the use of semidwarf material

Table 4. Estimated percent area planted to semidwarf wheat varieties

Region/country	Percentage of total wheat area	Year
Developing countries		
Sub-Saharan Africa	60	1994
West Asia/North Africa	42	1990
South Asia	91	1994
China	70	1994
Latin America	92	1994
High-income countries		
Australia	91	1994
Canada	3	1994
France	98	1994
United States	53	1993
Eastern Europe and the FSU		
Hungary	60	1994
Poland	100	1994
Russian Federation	30	1994

Source: Brennan and Fox (1995); CIMMYT (1993); CIMMYT (1996); Pardey et al. (1996).

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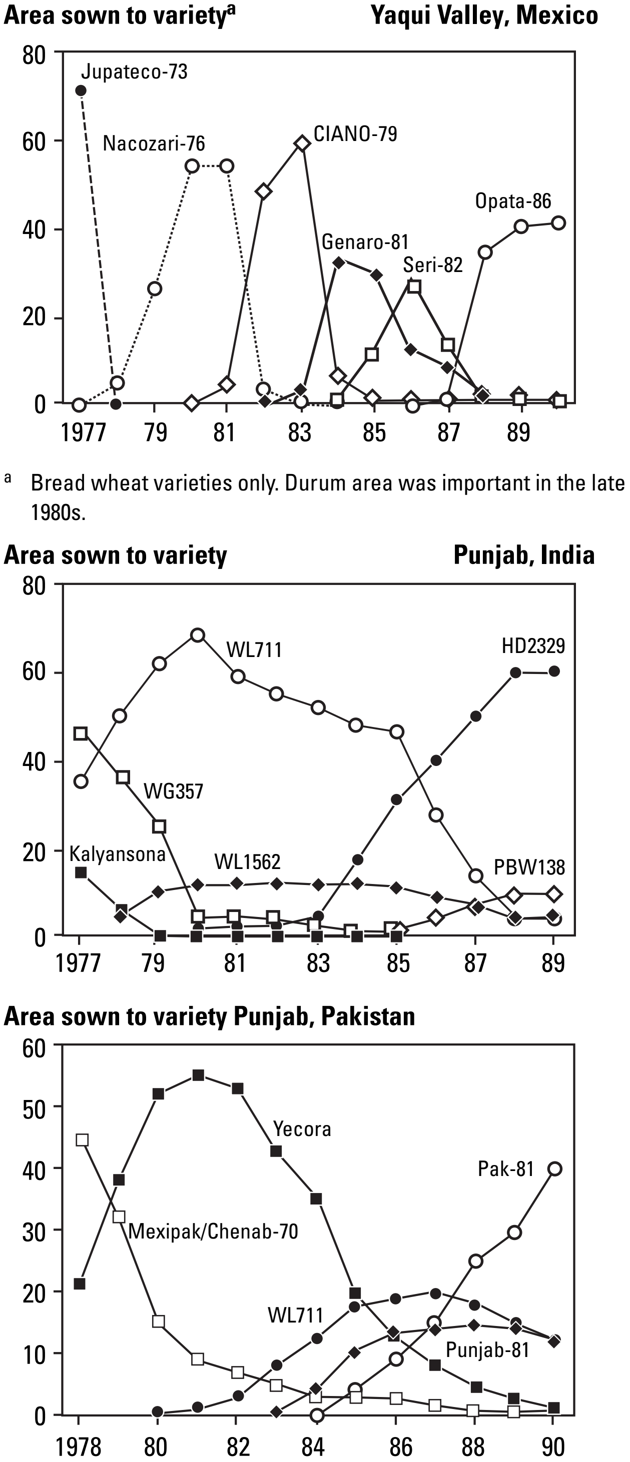
[6] Earlier wheat improvement efforts in both industrialized and developing countries provided gains in disease resistance, improved quality, and in some cases improved yield potential. This is treated in the text and in Appendix A. The most spectacular increases in yield potential in recent years generally have been associated with semidwarf varieties.

[7] In other words, CIMMYT germplasm has been incorporated into some recent Canadian releases for characteristics other than plant stature.

in Canada (Thomas 1996). In Europe, much of the semidwarf wheat sown in Mediterranean regions contains some CIMMYT germplasm, but semidwarf wheat sown at higher latitudes does not.

The countries of Eastern Europe plant 60–100% of total wheat area to semidwarf varieties (CIMMYT 1996). In the FSU, Desai (1992) and Morgounov (1992) reported that shorter stature varieties were cultivated during the 1980s, although tall varieties still predominate. Of the winter wheats grown in the FSU, tall varieties have tended to be more winter hardy than shorter varieties. As in Canada, problems associated with performance under dry conditions and photoperiod insensitivity constrained the immediate adaptability of CIMMYT materials in the spring wheat areas of the FSU (Morgounov 1992).

After initial adoption of the original semidwarf varieties in the 1960s, farmers have replaced the old MVs with newer generations of MVs. The period of replacement varies between regions, however (Heisey 1990; Morris, Dubin, and Pokhrel 1992; Byerlee 1994). Replacement is desirable because it enables farmers to avoid the gradual or sudden breakdown of disease resistance in older cultivars and to reap the benefits of traits bred into newer varieties (i.e., higher yield potential) (Bohn and Byerlee 1993). In the areas where the Green Revolution began, dominant Green Revolution varieties have been replaced at least once, and usually twice, since the first adoption of semidwarf wheat (Figure 2). In the Punjab of Pakistan, Mexipak, the original dominant semidwarf variety, was replaced by Yecora in the 1970s. Yecora, in turn, was replaced by WL 711, and especially by Pak-81 in the 1980s; and Pak-81 has now been displaced by Inqalab-91. Similar replacement of dominant and other varieties occurred in the Punjab of India and the



[a] Bread wheat varieties only. Durum area was important in the late 1980s.

Figure 2. Patterns of wheat varietal change in post-Green Revolution areas of Mexico, India, and Pakistan.
Source: Byerlee and Moya (1993).

Yaqui Valley of Mexico, although at somewhat faster rates (see Figure 2). Varietal replacement was also evident in China where initial semidwarf wheats imported from Pakistan and Mexico in the late 1960s were replaced by more locally adapted Chinese/ Chinese wheat crosses and Chinese/foreign wheat crosses in the 1970s. Other foreign sources of shorter stature wheat include Italian or Chilean cultivars descended from the short-strawed Japanese variety Akagomughi (Dalrymple 1986; Stone 1993; Yang and Smale 1996). The newer Chinese crosses evolved in response to difficulties encountered with the original imported varieties (i.e., susceptibility to rust, less tolerance to drought stress).

Varietal replacement has made a significant contribution to increased productivity in the past through g*enetic gains in yield,* which may be defined as the yield increase created by plant breeding and selection. These increases result from gains in yield potential, improved resistance to biotic stress (e.g., disease), or tolerance to abiotic stress (e.g., drought) (Byerlee and Moya 1993). Genetic gains in yield translate into gains in partial factor productivity (PFP), provided that farmers continually adopt newer varieties. They can also lead to improvements in total factor productivity (TFP).[8]

Byerlee and Moya (1993) have estimated annual genetic gains in yield of 0.5–1.5% for the majority of spring bread wheat environments in the developing world. In Appendix A, we expand upon Byerlee and Moya's summary by including studies of winter bread wheat and more studies from industrialized and developing countries.

Although this review is incomplete, and the methodologies used in all studies are not strictly comparable, several conclusions are possible. Wheat breeders have been successful in raising wheat yields in a wide range of environments and time periods. The most rapid increases in yields have often been associated with the switch to semidwarf varieties, although, in some locations genetic gains in yield were observed before semidwarf cultivars were widely used by breeders. Furthermore, in many cases breeders have continued to increase wheat yields in semidwarf varieties. Even when taking the dwarfing characteristic into account, it appears likely that improvements in disease resistance, improvements in lodging resistance, and increases in yield potential *per se*, have been the most important sources of genetic gains in wheat yield. Other things being equal, rates of genetic gains in yield have tended to be higher in more favorable, better-watered environments than in drier areas. In some cases, yield progress may have been slowed because of emphasis on other varietal characteristics, especially grain quality. Some studies have detected a possible leveling off of the rate of genetic yield progress in recent years, while others detect no such leveling. This question will be revisited later in this paper.

Byerlee and Moya (1993) also estimate actual gains from varietal replacement in farmers' fields in the developing world *after* the initial adoption of semidwarf wheat. During 1977–90, production increases from continuous varietal replacement of older MVs

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[8] We will consider changes in total factor productivity in greater detail below.

overtook the production gains generated by the original MVs. Gains from varietal replacement roughly accounted for two-thirds of the production increase attributed to breeding in that period (Table 5).

Varietal replacement has been made possible by the release of a continuous stream of newer and better adapted varieties. The varietal replacement necessary to maintain yield levels or to further genetic gains in yield depends on continued advances in wheat breeding research. Conventional wheat breeding research and emerging technologies related to wheat breeding (e.g., biotechnologies) will play an important role in maintaining productivity growth.[9] Future wheat research systems must be geared toward maintaining wheat breeding and strengthening crop and resource management research.

The time lag between varietal release and eventual adoption may also affect wheat varietal replacement and productivity in the future. The duration of the time lag in varietal replacement is heavily influenced by the economic policies and institutions that affect varietal diffusion, development of seed distribution systems, and development of related input delivery systems (as is the case in Pakistan [Heisey 1990]). These economic policies and institutions are factors that constrain or encourage adoption of new wheat cultivars; countries with slower rates of adoption will have lower genetic gains in yield.

Table 5. Estimate of the economic benefits of international wheat breeding research, 1977–90

	Sub-Saharan Africa	West Asia/ North Africa[a]	South Asia	Latin America	All
Increase in production (Mt)[b], 1977–90, when:					
(a) Farmers initially replace TVs with MVs					
Irrigated	0.00	0.10	1.94	0.12	2.52
High rainfall	0.09	0.46	0.00	1.09	1.69
Acid soils	0.00	0.00	0.00	0.40	0.40
Drought	0.00	0.21	0.13	0.31	0.65
(b) Farmers replace original MVs with newer generation MVs					
Irrigated	0.00	0.80	7.43	0.40	8.63
High rainfall	0.06	0.44	0.00	1.08	1.57
Acid soils	0.00	0.00	0.00	0.00	0.00
Drought	0.00	0.00	0.00	0.00	0.00
Total production increase, (a) and (b), 1990 (Mt)	**0.14**	**2.43**	**9.50**	**3.39**	**15.47**
Percent production increase due to replacement of TVs with MVs	**62**	**49**	**22**	**56**	**34**

Source: Byerlee (1994); Byerlee and Moya (1993).

[a] Excludes winter wheats.

[b] Mt = million metric tons.

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[9] A more detailed discussion of the role of conventional breeding and emerging technologies is found in the last section.

Fertilizer

Average fertilizer application levels in wheat vary by production system, geographical region, and income level. Today, the per hectare application of nitrogen in the high-income economies of Western Europe is the highest in the world, probably in part due to the land set-aside requirements, which motivates farmers to increase input intensity to compensate for smaller planted area. In 1990, nitrogen application to wheat ranged from 100 kg/ha to 190 kg/ha in Western Europe. Recent point estimates for 1990 (FAO/IFA/IFDC 1992; Martinez 1990) also show that farmers apply high levels of fertilizer (greater than 130 kg total nutrients/ha) to wheat in China, Egypt, Hungary, Mexico, India, and Zimbabwe. Use of nitrogen fertilizer among major wheat producers like Australia, Canada, Turkey, USA, and the Southern Cone of South America appears low to moderate, ranging from 8 kg/ha to 75 kg/ha in 1990 (FAO/IFA/IFDC 1992; Martinez 1990). Farmers in some countries of the FSU and Eastern Europe, such as the Russian Federation, Latvia, and Poland, also apply moderate to low rates of fertilizer to wheat (FAO/IFA/IFDC 1992; Martinez 1990). Following are more detailed observations on fertilizer application rates to wheat.

In the Yaqui Valley of Mexico, where fertilizer application rates have exceeded recommended levels, rates now appear to be leveling off. Fertilizer productivity (measured as a PFP index) fell during the 1980s, but there is no evidence of a further decline in the 1990s (Table 6).[10]

Table 6. Summary of farmers' production practices for wheat and wheat yields in the Yaqui Valley, Mexico, 1981–96

	Survey Year							
	1981	1982	1987	1989	1991	1994	1995	1996
Number of fields surveyed	**91**	**74**	**41**	**101**	**64**	**85**	**58**	**31**
Fertilization								
Nitrogen (kg/ha)	172	192	219	232	222	261	238	251
Phosphorus (kg/ha)	30	14	40	37	27	31	34	31
Total (kg/ha)	202	206	259	269	249	292	272	282
Pesticide application								
Herbicide (%)	59	53	44	47	44	21	38	32
Insecticide (%)	82	50	27	56	27	4	64	32
Planting method								
Broadcast	4	0	5	10	2	2	0	3
Bed/Row	6	8	37	37	53	60	83	84
Others (mainly row)	90	92	59	53	45	37	17	13
Yield (kg/ha)	4,748	na	6,105	5,163	4,660	5,468	4,911	5,353

Source: CIMMYT database; Institute of International Studies, Stanford University.

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[10] The simple calculation of a partial fertilizer productivity index by dividing yields by application rates (equivalent to dividing output by total nutrients applied) is problematic for several reasons. First, it assumes that crop yields are zero when no fertilizer is used (Chaudhary and Harrington 1993). Second, as with all partial factor productivity measures, it is an average measure when a marginal measure might have a more meaningful economic interpretation. Third, it obscures possible changes in technical efficiency as represented by a shift from MV'_1 to MV_2 in Figure 1.

Fertilizer use in South Asia expanded rapidly in the mid-1970s to the 1980s, a period of input intensification. In the technologically advanced area of the Indian Punjab, fertilizer use appears to have settled near the recommended level of 200 kg/ha of nutrients (Figure 3). Kumar and Mruthyunjaya (1992) found that fertilizer productivity (measured as a PFP index) in major wheat producing states in India declined in 1975–85, even though fertilizer use increased. A similar decline in fertilizer productivity has been reported for the rice-wheat systems of Pakistan during the 1980s (Ali and Velasco 1993). Caution, however, must be attached to these findings. Chaudhary and Harrington (1993) calculated partial fertilizer productivity for wheat in Haryana State in India during 1969–90 using the conventional method of dividing yield by application rate, and again by assuming wheat without fertilizer would yield at pre-Green Revolution levels. The first set of calculations showed the expected decline in PFP for fertilizer; the second, however, indicated that after an initial decline, fertilizer productivity in wheat stayed level and may even have increased slightly in the late 1970s and 1980s. The consensus view, however, is that over much of South Asia, most of the evidence suggests that diminishing marginal returns to increased fertilizer application were already apparent in the late 1980s (Byerlee 1992). This is consistent with the hypothesis that South Asia can be broadly classified as entering the Second Post-Green Revolution Phase in wheat production.

Fertilizer use for all crops in China rapidly grew in the late 1970s through the early 1990s (Stone 1993). In the northern provinces,[11] where wheat is the dominant crop, farmers' chemical fertilizer application averaged over all crops grew by 12.5% per year over 1965–90, from 9.4 kg/ha to 180 kg/ha (Fan and Pardey 1992). Manure, which remains an important source of nutrients, grew by a modest 1.7% in the northern provinces. The rapid increase in chemical fertilizer application may be due to increased fertilizer imports and larger fertilizer plant capacities resulting from institutional reform in the post-Mao era. According to Fan and Pardey (1992), although intensification in fertilizer use is expected to continue, diminishing marginal returns should soon become evident.

In the wheat producing countries of West Asia and North Africa (e.g., Turkey and Morocco), fertilizer use increased dramatically in the last two decades, but growth in recent years has slowed down, partially due to the removal or reduction of fertilizer subsidies (Belaid and Morris 1991; Morris, Belaid, and Byerlee 1991).

Aggregate fertilizer use in the FSU fell dramatically in the first years of the 1990s. As wheat is a major crop in much of the FSU, it is likely that fertilizer application to wheat has also been reduced significantly.

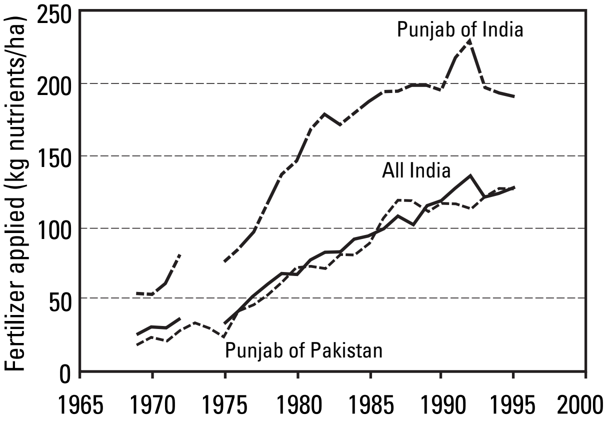

Figure 3. Estimated fertilizer use on wheat in India and Pakistan.

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[11] The northern provinces are Hebei, Henan, Shaanxi, Shandong, and Shanxi. They account for just less than half of China's wheat area.

Efficiency of fertilizer use may have been relatively low, suggesting that improved efficiency, rather than restoring earlier levels of application, may be crucial to raising yields in these countries (Liefert 1995).

In the major wheat producing states of the USA, both the proportion of wheat area fertilized and application rates per fertilized hectare increased over much of the 1960s and 1970s (Dalrymple 1980). In the last decade, application rates per fertilized hectare have remained relatively constant for the three major nutrients, nitrogen (N), phosphorus (in the form of P_2O_5), and potassium (in the form of K_2O). The proportion of wheat area receiving nitrogen expanded from slightly less than 80% to slightly less than 90% during this period, however, and the proportion receiving phosphorus grew from about 50% to about 60%. Aggregate application rates, averaged over all wheat area, have continued to rise (Table 7). The relative constancy in application rates in recent years suggests that US wheat producers may be approaching the Second Post-Green Revolution Phase. Improved nitrogen management, rather than increased nitrogen application, is now recommended to maintain productivity levels in wheat (USDA 1994).

In contrast to the USA, fertilizer application rates to wheat remain quite low in the dry environment of Australia,[12] despite the near-universal use of semidwarf varieties. For many years, phosphorus was the main nutrient applied to Australian wheat. More recently, there has been some expansion of nitrogen use in reaction to earlier expansion of wheat area at the expense of leguminous pastures that also served as rotation crops. Both nitrogen and phosphorus are still applied at low rates of roughly 10 kg/ha (Fischer 1996b).

Table 7. Chemical fertilizer application in wheat, United States, 1964–95[a]

		Application rates (averages over total wheat area)			
Year	Percentage area receiving fertilizer (%)	Nitrogen (kg/ha)	Phosphate (kg/ha)	Potash (kg/ha)	Total nutrients (kg/ha)
1964	50	14	–	–	–
1969	60	24	–	–	–
1974	65	33	–	–	–
1979	66	39	–	–	–
1985	77	52	19	6	77
1986	79	53	19	9	82
1987	80	56	20	7	82
1988	83	60	22	10	92
1989	81	56	22	9	88
1990	79	52	21	9	83
1991	80	56	22	10	87
1992	84	59	21	8	88
1993	87	62	23	7	91
1994	87	65	22	7	94
1995	87	62	23	8	93

Source: Dalrymple (1980); USDA (1994); USDA AREI (Agricultural Resources and Environmental Indicators) Updates, various issues.

[a] Seventeen major wheat producing states, 1964–79; fifteen major wheat producing states, 1985–95.

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[12] Nutrient-grain price ratios are also relatively high in Australia. See Table 6.

One indicator of the economic incentive for farmers to use fertilizer is the ratio of nitrogen price to wheat price at the farm level (Table 8). Among the countries for which data were available, high-income countries generally had higher ratios than countries of the developing world in the 1990s, except for the Southern Cone, a very commercialized wheat producing region. The ratio for the USA in the 1990s, for example, was above the observed ratios for major wheat producing regions of the developing world, such as China, India, Turkey, Pakistan, and Mexico. The higher ratio in high-income economies indicates that there are fewer incentives for increased fertilizer use in developed countries than in developing economies. High-income countries tend not to subsidize fertilizer inputs to encourage its use. The data are consistent with the hypothesis that farmers in high-income economies may be moving from intensive use of fertilizer toward more efficient technologies that will achieve desired yields while contributing to or maintaining the agricultural resource base.

Table 8. Nitrogen price to wheat price ratios at the farm level, selected years

Region	1981	1983	1985	1987	1990	1992	1994
Sub-Saharan Africa							
Kenya	–	4.5	5.2	2.3	2.5	3.0	4.8
North Africa							
Algeria	0.7	–	–	1.1	0.9	1.1	–
West Asia							
Turkey	–	2.6	2.3	3.6	1.6	1.6	3.6
Syria	2.0	2.1	1.4	0.8	1.5	1.3	–
South Asia							
Bangladesh	1.8	1.5	2.4	2.0	1.7	1.8	1.6
India	2.9	3.6	3.0	3.0	2.6	3.4	2.1
Nepal	2.7	2.7	–	2.8	2.9	3.3	2.1
Pakistan	2.2	2.3	3.7	3.0	3.0	2.9	2.5
East Asia							
China	2.8	2.5	1.7	2.7	2.6	2.8	1.9
Mexico and C. America							
Mexico	2.2	1.3	1.8	1.6	1.7	2.0	3.3
Southern Cone							
Argentina	6.3	7.8	5.0	8.1	7.6	6.1	5.8
Brazil	–	3.1	2.0	1.9	4.5	4.5	4.6
High-income countries							
Australia	–	5.4	8.0	7.0	5.4	7.0	5.5
Canada	–	–	4.0	4.4	5.3	–	3.9
France	–	3	3.4	4.6	3.6	–	4.3
USA	–	2.6	3.0	2.7	4.3	4.7	3.5
Eastern Europe							
Hungary	–	–	4.2	2.6	2.4	4.0	4.4
Poland	–	–	0.6	1.0	2.1	–	3.4

Source: *CIMMYT World Wheat Facts and Trends* (selected years).

In summary, without a change in the current technologies for producing wheat, fertilizer use in major wheat producing countries taken as a whole will probably grow at a slower rate, remain constant, or even decline in the medium term. Because yield gains from increased fertilizer use are diminishing, there are fewer incentives for farmers to intensify fertilizer application. Furthermore, if the predicted increase in real energy prices in the medium term holds, the resulting price increase in chemical nitrogen fertilizer may contribute to decreasing fertilizer application in wheat production (Byerlee and Saad 1993). The fertilizer subsidies implemented by most countries in the past, however, may remain instrumental in encouraging intensification.

There are likely to be differences among groups of countries in projected fertilizer use in wheat production, with leveling or declining use most likely in high-income countries. Despite slowing rates of growth in fertilizer use in developing countries, differences in application rates for similar environments within or across countries indicate that there is still potential for growth in fertilizer consumption. Although past application rates in the FSU may have been highly inefficient, current, exceedingly low fertilizer consumption in these countries suggests that even under a liberalized policy regime, fertilizer application to wheat will eventually rebound.

Irrigation

In addition to fertilizers, irrigation investments have contributed heavily to yield growth in the past, especially in developing countries. In South Asia, for example, large investments in irrigation during the 1960s and 1970s were a major factor behind growth in wheat yields during those decades. Irrigation played a relatively minor role in high-income economies compared to developing economies. Better moisture conservation practices may have contributed more to yield growth in high-income countries.

Growth in irrigated wheat area reflects the ongoing conversion of rainfed land to irrigated land and the importance of irrigation in wheat production systems (Hobbs and Morris 1996). In India, irrigated wheat area remained fairly constant at one-third of the total wheat area throughout the 1950s. Starting in the 1960s, the percentage of irrigated wheat area began to grow until it reached 83% of the total area by 1992, as irrigation facilities became available on formerly rainfed land (Figure 4) and wheat was substituted for other crops on irrigated lands (Byerlee 1992). Growth in the expansion of irrigated lands, however, began to slow in the 1980s because the more favorable sites had already been developed. In the Yaqui Valley of Mexico, 100% of the wheat area is irrigated.

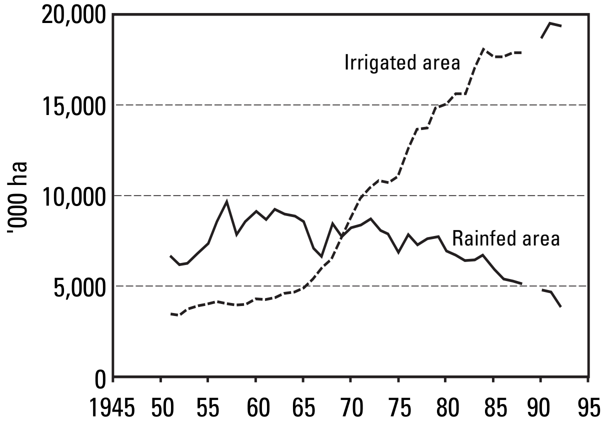

Figure 4. Trends in rainfed and irrigated wheat area in India, 1951-92.

Available data for China do not explicitly indicate the percentage of wheat area that is irrigated, although a point estimate indicated that in the mid-1980s, 31% was irrigated (CIMMYT 1989a).[13] This may, however, be a serious underestimate (S. Rozelle, personal communication). In the major wheat producing provinces of China, *total* irrigated area marginally increased from 49.2% of arable land in 1980 to 52.3% in 1990 (Fan and Pardey 1992). Growth in total irrigated land has been relatively slow since the mid-1970s, and changes in level of irrigation have played a very minor role in total cereals yield since then. Inefficiencies in irrigation systems have led to problems such as salinity (Huang and Rozelle 1995).[14] Trends for irrigated wheat are not expected to differ significantly from trends for all cereals production in China. This suggests that in the future, rehabilitation and better management of existing irrigated systems may play a larger role than expansion of irrigated area.

In West Asia and North Africa, irrigated wheat still represents a small proportion (20%) of total cultivated area planted to wheat (Morris, Belaid, and Byerlee 1991). In the southern republics of the FSU, winter wheat is not usually irrigated, because it can efficiently use residual moisture from snow and because other crops (e.g., vegetables and cotton) were given priority by the government in the past (Morgounov 1992). In the USA, irrigated land in wheat rose from 0.8 million ha in 1969 to a peak level of 1.9 million ha in 1982 and then decreased to 1.6 million ha in 1993. There has been little change in irrigated land as a percentage of total wheat area in the last decade. For all US crops, the amount of water applied has declined since the late 1960s, suggesting that farmers are looking toward improving irrigation efficiency to decrease nitrogen leaching, reduce soil erosion, and improve plant nutrient uptake (USDA 1994).

Worldwide, over the medium and long term, investments in wheat irrigation are expected to decline. There are several disincentives for the expansion of irrigation investments. First, the net economic costs of additional irrigation have been rising and are expected to continue to rise due to managerial inefficiencies in publicly built systems and because the most favorable sites have already been developed. There have been initiatives, however, to alleviate rising costs and improve irrigation delivery through small-scale irrigation projects and participatory institutional mechanisms (Ostrom, Schroeder, and Wynne 1993; Rosegrant and Svendsen 1993). Second, many irrigation systems have become degraded through lack of maintenance, and most irrigation investments in developing countries are devoted to rehabilitating existing systems rather than constructing new ones. Furthermore, competition from urban and environmental users of water is expected to increase sharply in all countries, adding more pressure on the water supply for agricultural uses (Crosson and Anderson 1992; Hobbs and Morris 1996). Opportunities for profitable investment still exist, but as Rosegrant and Svendsen (1993) point out, improved impact assessment procedures will be needed to identify cost-effective intervention points.

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[13] Another 55% of the wheat area in China was classified as relatively favorable (> 500 mm rainfall over the growing season) for rainfed wheat.

[14] Henan and Hebei, two of the most important wheat growing provinces in China, are also among the provinces most affected by salinity (Huang and Rozelle 1995).

Pesticides and Mechanization

Pesticides and agricultural mechanization are two other inputs that contributed to past yield growth. In general, and specifically for developing countries, less pesticide is applied (fungicides, insecticides) to wheat than many other crops because of the high levels of disease resistance bred into MVs. Herbicides, however, are more widely used. In the Punjab of India, for example, herbicide use substantially increased in the 1980s in response to widespread losses caused by the weed *Phalaris minor* (Sidhu and Byerlee 1992). In contrast, survey data demonstrate that the application of herbicides by farmers in the Yaqui Valley of Mexico has been decreasing since 1981 (Table 6). Herbicide applications are being replaced by other crop management techniques such as integrated pest management (IPM) and alternative methods of weed control made more feasible by the shift to bed planting (Traxler and Byerlee 1992a).

In the USA, other field crops such as maize, soybeans, cotton, and potatoes receive more pesticide than wheat (USDA 1994). Total pesticide applications to wheat have fallen by about 40% over the past 20 years. Both herbicide and insecticide use in the USA peaked in the mid-1970s, followed by lower, more stable levels in the early 1990s (Table 9).[15] US wheat farmers may be moving away from intensive use of pesticides, which is consistent with the hypothesis that they are in a stage of increasing technical efficiency.

Increasing awareness about the negative effects of chemical pesticide application and the consequent promotion of integrated pest management (IPM) techniques, together with the data above, may imply that global pesticide applications in wheat could decline in the future. Globally, herbicide will remain the most common pesticide applied to wheat. However, factors such as price incentives, level of pest incidence, and technological breakthroughs with regards to pest resistance or crop management, may have unpredictable combined effects on future pesticide use and may result in variations in use levels among regions.

Table 9. Estimated quantity of pesticide active ingredients applied to US wheat, selected years (in 000 kg)

Year	Herbicides	Insecticides	All pesticides
1964	4,163	404	4,567
1966	3,741	397	4,159
1971	5,272	777	6,159
1976	9,924	3,282	13,597
1982	8,856	1,294	10,643
1990	7,548	440	8,066
1991	6,151	94	6,279
1992	7,892	523	8,939
1994[a]	7,248	704	8,318
1995[a]	6,905	316	7,397

Source: USDA (1994); USDA AREI (Agricultural Resources and Environmental Indicators) Updates.

[a] Totals for major wheat producing states only.

Machinery use in the Punjab of India and Pakistan substituted rapidly for human and animal labor in the 1970s to the 1980s (Byerlee 1992; Sidhu and Byerlee 1992). Various policies (i.e., subsidized credit) and real shifts in relative factor prices of labor and draft power encouraged this change. In the Yaqui Valley of Mexico, the steady change of planting method to row planting on beds and an increase in machinery ownership may suggest the substitution of more machinery for farm labor in the last 15 years (Table 6; Traxler and

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[15] In recent years, herbicide application rates in the USA have been higher in the spring wheat areas of the northern Great Plains than in the winter wheat regions in the central and southern Plains. Insecticide use has been most common in the winter wheat growing states of Oklahoma, Texas, and Colorado.

Byerlee 1992a). Alternatively, the incidence of hand weeding in the Yaqui Valley has also increased during this period. In major wheat producing provinces of China, machinery use (as measured by horsepower per agricultural worker) rapidly increased during 1965–90 (Fan and Pardey 1992); however, this may have been a reflection of the deliberate policy bias in favor of capital-intensive development strategies more than changes in real factor prices.

Because wheat production in most developing countries remains relatively labor intensive, higher wage rates provide continued incentives for substitution of machinery for labor. In many high-income countries, by contrast, land-saving crop management methods may now be substituting for excessive machinery use. For example, data for US field crops indicate that machinery purchases have declined and conventional tillage with moldboard plows has fallen as mulch-till and no-till systems have expanded in area. These trends, however, have been much less common in wheat than in other crops such as maize and soybeans. Even for wheat, these trends have been less common in the major wheat producing states than in states where wheat is more frequently grown in rotation with other crops. In the major wheat producing states, moldboard plowing has generally been displaced by other conventional tillage methods (USDA 1994).

Changes in Efficiency of Input Use

Previous sections of this paper surveyed past increases in wheat production and outlined patterns of input use. Increased use of some inputs, such as fertilizer, irrigation, and machinery, have led to greater wheat output. Other inputs, specifically semidwarf wheat varieties, have shifted the yield frontier, making possible higher wheat yields using the same amounts of fertilizer and water. Meanwhile, other inputs, such as pesticides, have protected against yield losses. In this section, available data on the efficiency and productivity of major wheat producing regions are presented. This will allow an assessment of allocative and technical efficiency in wheat production and the role that sustainable management practices may play in the efficient production of wheat in the future.

Allocative and Technical Efficiency Estimates

In microeconomics theory, allocative efficiency of input use is usually distinguished from technical efficiency. The process of moving toward allocative efficiency is usually accomplished by equating the marginal value product (MVP) of purchased inputs to their acquisition prices, based on available information. Achieving technical efficiency generally refers to increasing the quantity of physical output for a given level of input use. Technical efficiency may be increased by greater use of non-purchased inputs such as knowledge and management skills.

Inefficiencies in input use, whether allocative or technical, are often associated with inadequate information (Byerlee 1987; Ali and Byerlee 1991). More complete information about input and product markets can improve the allocative efficiency of farmers; greater access to crop management information can increase their technical efficiency. The transmission of price information relevant to allocative efficiency may be accomplished through markets. Communicating technical information, however, may not be as straightforward. This is one reason why the conceptual framework presented earlier concentrated on allocative efficiency before technical efficiency. Nonetheless, because available technical and price information continually changes, the processes of improving both allocative and technical efficiency often overlap; simultaneous adjustments may be made in improving both types of efficiency as information becomes available. For expositional convenience, the process of attaining allocative efficiency was presented before that of attaining technical efficiency.

Before briefly reviewing some of the studies of allocative and technical efficiency in wheat production, it should be quickly noted that one major empirical issue has not been widely treated in the literature: "Knowledge-intensive" technology in crop management that might improve efficiency may also require greater amounts or more precise timing of labor, at a time when rural wage rates are rising. Similarly, the education that increases a farmer's technical or allocative efficiency might also increase the opportunity cost of using those management skills on the farm (Pingali 1997). Therefore, it is difficult to predict *a priori* the net effects of investments and policy changes aimed at increasing farmer efficiency.

Allocative efficiency has often been measured by comparing the MVP of an input to its price as a ratio K, although in some cases a profit function or profit frontier has been employed. For wheat in South Asia (summarized in Table 10), allocative efficiency studies reveal an average K value well above 1.0, but results vary widely for different inputs; for instance, from 0.8 for bullock labor in India to 13.5 for fertilizer inputs in Pakistan. In general, studies of allocative efficiency in developing country agriculture have been highly conservative, accepting the null-hypothesis that farmers are efficient in allocating their resources, despite the fact that most estimated K values far exceed unity (Shapiro 1983; Byerlee 1987; Ali and Byerlee 1991).[16] Only a few studies, such as those by Shapiro (1983) and Junankar (1980), have rejected the hypothesis that farmers are allocatively efficient in using their resources.

Technical inefficiency, measured indirectly, is more frequently used in the literature than direct estimates of technical efficiency.[17] There are no apparent empirical regularities in the direct technical inefficiency estimates reviewed from various studies. The estimates vary for each major wheat producing region, ranging from 11% to 31% (Table 10). Rather than directly estimating technical efficiency, some studies measured the effect of non-conventional inputs, such as education, on technical efficiency. Those studies generally found that an additional year of education may increase productivity in wheat producing areas by at least 1%, especially in South Asia.

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[16] This may reflect the influence of the "poor but efficient" hypothesis of Schultz (1964). Schultz (1964, 1975) recognized a continuum between the development of new technology and "the more efficient use of available technology and resources at the farm level" (Ali and Byerlee 1991). See also Ball and Pounder (1996), who argue that Schultz' contribution was more an emphasis on the "dynamic responsiveness of farmers rather than the static efficiency of a traditional equilibrium."

[17] There are two common approaches to estimating technical inefficiency. In the "frontier approach," technical inefficiency is measured using a two-stage process by estimating a production function using the most efficient set of inputs and outputs, and then measuring the deviations from this frontier (see Huang and Bagi 1984; Hussain 1989). In the "non-frontier/direct approach," technical inefficiency is measured by incorporating the "non-conventional inputs" within the production function and estimating directly the effects of these variables on technical efficiency (see Salam 1976; Butt 1984; Jamison and Moock 1984; Feder, Lau, and Slade 1987; Azhar 1991). For a comprehensive review of the two methods and a presentation of some empirical examples, see Ali and Byerlee (1991) and Battese (1992).

Table 10. Summary of studies estimating allocative and technical efficiency in wheat production

Source, location, and year of study	Main findings with regards to efficiency
Allocative efficiency studies Sahota, 1968 *(Uttar Pradesh and Bombay, India)*	Estimated an average K value of 0.8 for bullock labor and 1.05 for fixed capital.
Barnum and Squire, 1978 *(India)*	Estimated a K value of 2.7 for variable inputs (presumably fertilizer) and concluded that the farmers were allocatively efficient.
Hussain and Young, 1985 (*Pakistan*)	Estimated a K value of 13.5 and 1.8 for fertilizer and irrigation inputs, respectively.
Bliss and Stern, 1982 *(Palanpur, India)*	Estimated a K value of 3.5 for fertilizer inputs.
Technical efficiency studies Parikh, Ali, and Shah, 1995 *(Northwestern Pakistan)*	Technical inefficiency estimated at 11.3%. At the aggregate level, inefficiency was attributed to underuse of hired labor, fertilizer, manure, as well as the overuse of animal labor.
Hussain, 1989 *(Northern Pakistan)*	Technical inefficiency estimated at 31%. Factors that significantly influence efficiency are new seed, seed treatments, density, and knowledge score.
Johnson et al., 1994 *(Ukraine)*	Technical inefficiency estimated at 13–16% for grain farms (including wheat) from 1986 to 1991.
Aly et al., 1987 *(Illinois, USA)*	Total combined inefficiency estimated at 42%, with 25% attributed to technical inefficiency.
Huang and Bagi, 1984 *(Haryana, India)*	Technical inefficiency estimated at 11%, but did not explain sources of inefficiency.
Fan, 1991 (*Northern China)*	Technical inefficiency estimated at 28% in 1985.
Azhar, 1991 *(Pakistan)*	Estimated that one additional year of schooling leads to a 1.28% increase in farm output of farmers using modern varieties.
Butt, 1984 *(Irrigated Pakistan)*	Primary education increased productivity 7% and secondary education by 10.7%. Strong positive interaction of education and fertilizer use.
Jamison and Moock, 1984 *(Nepal)*	Completion of at least 7 years of schooling increased productivity in wheat by 27–31%.
Pudasaini, 1976 *(Bara District, Nepal)*	An additional year of education was found to increase output by 1.3%. The coefficient of education on agricultural productivity was estimated at 1.4%.
Feder, Lau, and Slade, 1987 *(Haryana, India)*	Education increased wheat productivity by 1% per year of schooling. The training and visit extension system also increased productivity by 9%.
Sidhu and Baanante, 1979 *(Punjab, India)*	An additional year of farmer education makes an estimated contribution of 1.7% in wheat production. Coefficient of education on agricultural productivity estimated at 3.6%.
Chaudhri, 1976 (*Punjab, Haryana, and Uttar Pradesh, India*)	Coefficient of education on agricultural productivity estimated at 11.5%. Estimated increase in output per additional year of education was 6.47%.
Yotopolous, 1967 *(Greece)*	The coefficient of education on agricultural productivity was computed as 13.8%.

Source: From own research and Ali and Byerlee (1991).

In general, most of the efficiency studies on wheat conclude that lack of technical knowledge and education are primary sources of technical and allocative inefficiencies. This implies that increasing the efficiency of input use by improving farmer knowledge and skills can potentially increase productivity growth in the medium to long term, with the caveat that current information about the net effect of these measures in areas characterized by rising real wage rates and substantial off-farm work is inadequate. In studies based on cross-sectional survey data, the estimated effects of farmer knowledge and skills on the efficiency of wheat production also vary widely, depending on the location and time of the study. In countries such as China and those of the FSU, governmental reforms of institutions, too, may have a significant effect on wheat production efficiency.

Few empirical estimates for allocative and technical efficiency of wheat inputs have been developed to provide time-series data on efficiency parameters. Such studies are crucial for answering questions about whether inefficiency is decreasing over time with increasing levels of farmer education and experience or whether continued technical change has led to recurring disequilibrium. In addition, there are numerous conceptual and methodological problems associated with estimating allocative and technical efficiency (Ali and Byerlee 1991). For research and estimation purposes, Ali and Byerlee (1991) even suggested that the distinction between allocative and technical efficiency may not be very meaningful because the partitioning of the two factors is sensitive to the level of input aggregation used in the modeling process. The distinction may be important, however, from a policy standpoint.

Factor Productivity Indices

Given the limited time-series estimates of technical and allocative efficiency, factor productivity indices can be used to describe the pattern of input efficiency for a certain location over time and, therefore, serve to complement the allocative and technical efficiency estimates summarized earlier.

Partial factor productivity indices, which relate changes in output to changes in the use of individual inputs, have been discussed in the context of individual inputs such as fertilizer. This approach is taken one step further in a noteworthy study that provides a comprehensive analysis of wheat yield in the Punjab Province of Pakistan (yield is a partial productivity measure for land) by Byerlee and Siddiq (1994). They disaggregated the effects on wheat yields of three factors: (1) initial adoption of MVs, (2) replacement of old MVs with newer MVs, and (3) increasing fertilizer application. After the positive effects of these three factors were accounted for, estimated wheat yield trends showed a significant negative residual, suggesting that other factors were responsible for a long-term decline in yields (and productivity). They concluded that long-term negative influences on wheat yields are present and that gains in productivity would not continue once the gains from the three disaggregated factors have been exhausted, unless other factors contributing to long-term yield trends (i.e., resource/input management, development of technology) are properly addressed. The reasons behind the negative influences have not been definitively ascertained, but several explanations relating to agricultural resource degradation have been put forward. Agricultural resource problems relating to wheat production are discussed further in the following section.

Total factor productivity indices are constructed as the ratio of an output index to an index summing all inputs.[18] A TFP that rises over time is interpreted as evidence of productivity growth that can be attributed to factors other than increasing quantities of inputs. Such factors include technological change, efficiency in the application of inputs, and changes in the quality of inputs. In recent years, TFP indices have also been used as indicators of long-term sustainability in agricultural systems (Lynam and Herdt 1989; Byerlee 1994; Hobbs and Morris 1996). Murgai (1997), however, cautions that the assumption of profit-maximization necessary to conduct TFP analyses implies that they are more suitable for analyzing productivity growth than sustainability. For analyzing sustainability, correcting for price distortions or the use of unpriced natural resources would require that the analyst observe not only shadow prices, but the quantities of inputs that producers would use if faced with these shadow prices.[19]

The South Asian experience is a pertinent example for examining recent trends in factor productivity of wheat. Sidhu and Byerlee (1992) estimated productivity changes for wheat in the Indian Punjab during the 1970s and 1980s. They concluded that productivity gains of 2% per year were achieved over the period of analysis (Figure 5). These productivity gains can be attributed in roughly equal proportions to the adoption of land-saving technologies (MVs and fertilizer) and labor-saving technologies (e.g., machinery). Most of the gains in productivity occurred over the second half of the period, during the Post-Green Revolution Phase, lending strength to the argument that input intensification was the primary source of output growth during the Green Revolution. This conclusion is supported by Murgai (1997), who also argues that in the Post-Green Revolution Phase, greater efficiency in input use may have spurred productivity growth.

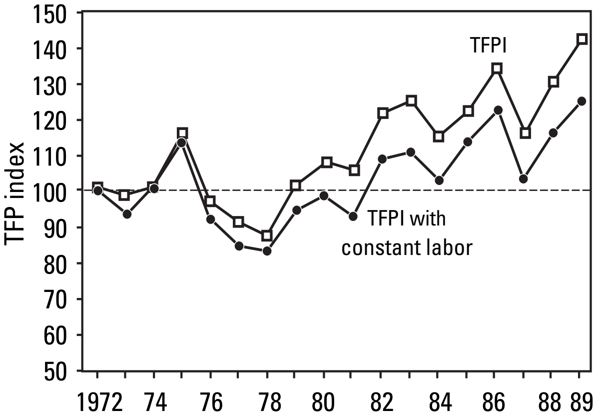

Figure 5. Index of total factor productivity (TFP) in wheat production, Punjab, India, 1972–89.
Source: Sidhu and Byerlee (1992).

Sidhu and Byerlee warned that future sources of productivity gains capable of increasing TFP at rates equal to those achieved in the past are not evident. Levels of input use are already high, and the gap between the highest and lowest wheat yields obtained by farmers is narrowing (Singh, Singh, and Bal 1987), as is the difference between yields in farmers' fields and at research stations. Further productivity gains in wheat production, therefore, will depend on even more efficient use of inputs, increasing access to information, and improving the management skills of farmers.

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[18] If wheat production alone is studied, and wheat grain is considered the only product, the output "index" might consist solely of the value of wheat production.

[19] This would seem to imply that the analysis would require direct estimation of the production function besides some means of determining shadow prices.

Kumar and Mruthyunjaya (1992) expanded on Sidhu and Byerlee's study (1992) by considering wheat producing regions in India other than the Punjab. During 1970–89, they found that TFP indices grew annually by 1.9% in Punjab, 2.7% in Haryana and Rajasthan, 2.6% in Uttar Pradesh, and 0.4% in Madhya Pradesh. The authors also decomposed the TFP estimates to identify the sources of growth and found that market infrastructure, mechanization, and research were the most important factors. They concluded that further productivity gains in wheat could be achieved through more efficient use of inputs such as fertilizer, water, and machines—consistent with the results of Sidhu and Byerlee (1992). As research was an important source of growth, the authors also indicated that new varieties capable of breaking the current yield ceilings will be instrumental in the future productivity of Indian wheat farmers.

A recent policy brief by Kumar, Rosegrant, and Hazell (1995) concluded that TFP growth for wheat in India dropped from 1.4% per year in the 1970s to 1.1% per year in the 1980s. This decline was attributed to declining real investments in agriculture, such as research. Projected future wheat supply was estimated to meet long-term demand, provided that productivity is maintained through public investment in irrigation, infrastructure development, research, and efficient use of water and plant nutrients. These recommendations are also consistent with the cited studies.

The conclusions reached in studies of TFP for rice-wheat systems contrast with those reported in studies of wheat productivity alone. For Pakistan's rice-wheat systems of the Punjab and Sind Provinces, Ali and Velasco (1993) found that TFP indices declined during the 1970s and 1980s, with a faster rate of deterioration (more than 2% per year) during the second half of the period. Cassman and Pingali (1995) also calculated declining productivity indices for the rice component of the rice-wheat systems of the Ludhiana district of the Indian Punjab. According to their estimates, TFP steadily increased during the 1970s and leveled off for awhile before slowly dropping. Both studies attributed the decline in TFP to deterioration of agricultural resources, especially the soil. Clearly, proper management of agricultural resources is also essential in the medium- to long-term productivity of wheat-based cropping systems.

In China, another major wheat-producing developing country, Fan (1991) estimated that TFP growth for the dominant wheat producing provinces rose by 2.8% annually during 1965–85. Fan attributed more than 90% of this growth in productivity to institutional change (e.g., market reforms and the household production responsibility system) in the post-Mao era. Technical change contributed only about 10% of the productivity growth during this period, which suggests that there is potential for Chinese farmers to improve productivity by applying more efficient input technologies.

Tyers (1994), in his study of the potential effects of reforms on agriculture, provided some wheat productivity estimates for the countries of Eastern Europe and the FSU. Productivity growth for wheat was negative in both regions between the late 1980s and the early 1990s. Countries of Eastern Europe experienced productivity declines ranging from 2% to 9% over this period. Wheat productivity fell by 14% in Russia and Ukraine, and by 38% in Kazakstan. Tyers attributed the negative estimates to government's failure to generate and adopt technology in the agricultural sector and to the policy bias favoring livestock production over grain production. Productivity in wheat marginally improved in both regions after market reforms were implemented and price distortions removed. Further modest improvements in wheat productivity are possible, but much depends on institutional and political developments in the region.

Total factor productivity indices for the USA are usually calculated for the agricultural sector as a whole and not specifically for wheat production systems. However, these growth rates are important as a basis for comparing the TFP rates in wheat for other countries. Capalbo and Vo (1988) estimated a growth rate in TFP of 1.57% for US agriculture from 1950 to 1982. Luh and Stefanou (1991) also dynamically measured a similar TFP growth of 1.5% for the same period. Jorgenson and Gollop (1992) found a similar growth rate of 1.58% for 1947–85. If these US estimates serve as a benchmark for productivity, past TFP patterns for wheat in other countries indicate comparable performance, except for the FSU and the rice-wheat systems of India and Pakistan. It follows that if practices leading to intensification of input use rather than more efficient use of inputs continue to dominate, factor productivity may decline in the medium to long term.

Sustainability Issues

Future yield growth also depends on the capacity of farming systems to achieve stable gains in productivity over the long term while maintaining or even enhancing the quality of the agricultural resource base. Defined in this way (Lynam and Herdt 1989; CIMMYT 1989b; Byerlee 1992; Fischer 1994), sustainable agriculture critically depends on continued productivity increases and vice versa.

Broadly speaking, the quality of the agricultural resource base can be viewed as an input. The proper management of this input may improve future yield levels. Thus, the farmer is faced with an intertemporal problem in which he or she must choose a management strategy that will maximize economic returns over time. In theory, this requires the full valuation of agricultural resources in a dynamic context, which is not realistically possible. Since we know, however, that today's resource use affects tomorrow's available resources, using sustainable resource-conserving practices as a management strategy can be consistent with intertemporal revenue maximization. Proper management of the resource base, therefore, is an important aspect of improving technical efficiency of inputs over time.

Agricultural resource degradation has already been cited as the possible source of slower yield growth experienced by farmers in developing countries in recent years (Ali and Velasco 1993; Byerlee and Siddiq 1994; Cassman and Pingali 1995). Resource problems that may cause productivity declines are often site specific, varying between and within regions. An examination of Australian wheat production systems, for example, indicates that their agricultural resource problems are less critical than those faced by farmers in South Asia (Fischer 1994). The Australian example also indicates that continued research efforts aimed at counteracting the effects of agricultural resource degradation provide payoffs in the form of greater sustainability. The resource problems discussed below are global in scope and may affect countries or regions with varying levels of severity.

The degradation of agricultural resources usually stems from three major sources: (1) soil problems, (2) water problems, and (3) pest problems. Soil problems, cited most frequently as possible causes for productivity declines, are often attributed to unbalanced soil chemistry, because continuous wheat cropping systems are heavy extractors of soil nutrients. Although this conclusion seems inescapable, evidence is insufficient to clearly link productivity declines to decreased soil fertility, partly because many farmers (especially in technologically advanced areas) have applied fertilizer nutrients like nitrogen and phosphorus at close to recommended levels. It is also suggested that micronutrient deficiencies (zinc, boron, and manganese) are a yield limiting factor, but yield experiments with these nutrients have rarely given conclusive results (Hobbs and Morris 1996). Organic matter also plays a role in balancing soil chemistry, although it is not yet fully understood. In major producing areas, soil acidification and salinization are also important factors that may have contributed to past yield declines (Fischer 1994).

Physical soil problems can also contribute to reduced wheat productivity through poor soil structure (due to soil compaction), waterlogging, and root-restricting soil layers. Increased cropping intensity and excessive or inappropriate tillage practices may have contributed to these problems. Another often forgotten factor is soil microbiology. Experiments in developing countries show that interactions between organic matter and soil microbes contribute to the soil's natural ability to provide nitrogen. Research in Nepal also shows that underground pathogens may contribute to wheat yield declines in the area (Dubin and Bimb 1994; Cassman and Pingali 1995; Hobbs and Morris 1996).

Declining availability and quality of water resources are emerging problems in irrigated wheat cropping systems of the world. The quantity of water available for production is already a problem in many regions of South Asia due to declining water tables, particularly areas where tubewell irrigation has become more prevalent (Harrington et al. 1993; Hobbs and Morris 1996). Declining water tables raise production costs (by forcing farmers to pump water from greater depths), while prompting questions about the future availability of water resources to maintain current levels of productivity.

In other regions, water tables have risen rather than fallen, but the quality of irrigation water has become a problem; in South Asia, especially, water-borne salts and minerals have increased soil salinity and sodicity. Salinity and sodicity harden the topsoil, reduce plant stand (through poor seed emergence), and reduce water infiltration, all of which contribute to decreases in productivity.[20]

Besides issues of water quantity or quality that can directly affect on-farm productivity, the heavy use of chemicals in intensive agriculture can also lead to off-site water pollution problems. Singh, Singh, and Bal (1987) indicated that nitrate contamination of groundwater in the Indian Punjab substantially increased water quality degradation in the past. In Australia and Mexico, nitrate leaching is also becoming a major resource problem (Fischer 1994).

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[20] For example, a few districts of the Indian Punjab that have relied more heavily on canal irrigation than groundwater in the past have recently placed more land under the rice-wheat rotation. These districts have particularly severe salinity problems (Murgai 1997).

Increased intensification and continuous cropping patterns of wheat have increased the incidence of pest problems, especially weeds. In South Asia, *Phalaris minor* has become a significant weed problem in wheat production systems. Left unchecked, it has the potential to cause 100% yield loss (Hobbs and Morris 1996). Chemical control, the most common practice in lieu of ineffective hand weeding, creates additional resource problems when harmful chemicals leach into the soil and water table. There is also evidence that intensified chemical application has caused weeds to develop resistance to common herbicides, which may adversely affect future productivity. In Australia, herbicide-resistant weeds, such as *Hordeum*, *Lolium*, and *Avena spp.*, have already been recognized (Fischer 1994).

Disease and insect problems are relatively less important in wheat production than in many other cereals. Disease resistant MVs have contributed to alleviating the problem of disease infestation. Increasingly, wheat scientists attempt to accumulate diverse multiple genes for resistance from new sources and genes that control different mechanisms of resistance within single varieties. Today, many of the world's major varieties contain resistance genes for stem and leaf rust, with effects that are likely to be or have been long lasting (Singh and Rajaram 1991; Singh 1993;Van Ginkel and Rajaram 1993). Progress with stripe rust has been less pronounced to date. Modern varieties that are resistant to pests enhance the resource base by decreasing the need and use of chemical pesticides that may harm soil and water resources. Even for diseases for which long-lasting sources of resistance are available, resistance may break down due to lack of diversification in farmers' fields.

Future improvement in wheat productivity critically depends on properly managing the agricultural resource base by using technically efficient farm practices. Many of the solutions for both sustainability and efficiency problems are embodied in more efficient input use (through improved management practices) and continuous varietal replacement (through wheat breeding technologies).

Improved management practices contribute to productivity and sustainability by efficiently using inputs while not incurring harm to the resource base. Integrated pest management, for example, contributes to sustainability by reducing the volume of harmful chemicals released into the environment. It also contributes to input efficiency by using the optimal level of pest control. Optimal timing of nitrogen fertilizer application may help reduce nitrate leaching by promoting efficient plant utilization of soil nitrogen. Conservation tillage and proper crop residue management are other practices that contribute to sustainability by promoting better soil fertility and structure. Improved plant density and canopy cover are management practices that may help lower weed infestation, which, in turn, may lower chemical herbicide applications that can harm the resource base (Meisner et al. 1992). The challenge of developing sustainable resource management practices for wheat is to find practices that lessen resource degradation without lowering yields or raising costs.

Advances in breeding for resistance and stress tolerance, in addition to ongoing varietal replacement, will continue to contribute to more efficient and sustainable systems. Pest resistant MVs help alleviate resource problems by reducing harmful chemicals in the soil and promoting the use of sustainable practices (i.e., IPM), while maintaining yield levels. MVs that are tolerant to abiotic stress may contribute to sustainability and potentially lead to greater productivity by ameliorating nutrient depletion pressure in the soil and tolerating drought stress and soil toxicities (see Byerlee 1994). New varieties with root characteristics that reduce nitrogen leaching in the soil may improve the resource base while maintaining current yield levels (Fischer 1994). Nutrient mining may also be alleviated when MVs are developed to improve nutrient use efficiency, especially for major nutrients like nitrogen and phosphorus. For the last 30 years, for example, successive generations of spring bread wheat varieties based on CIMMYT germplasm have required smaller amounts of nitrogen to meet the same level of wheat output (Waggoner 1994; Ortiz-Monasterio et al. 1996).

Although improved management practices and more input-efficient varieties can contribute to the sustainability of the resource base, they may not be able to overcome the negative effects of output or input price subsidies that encourage overuse of agricultural inputs. These and other policy issues are discussed in the following sub-section.

Policy Issues

Future productivity growth in wheat and a reduction of the burden on the agricultural resource base will depend on improving management practices designed to increase the efficiency of input use (Byerlee 1992; Byerlee and Pingali 1995). Management gains in wheat are projected to be one of the constant factors contributing to productivity growth until the year 2020 (Evenson and Rosegrant 1995). Simply put, information and knowledge, rather than the conventional inputs of water, fertilizer, and machinery, will become increasingly important. These are the major factors that will be required to obtain the gains in the input efficiency stage of technical change (Byerlee 1992).

In the USA, further gains can be attained in fertilizer and chemical efficiency in various crops, including wheat and maize, through the application of "high precision farming" techniques (Munson and Runge 1990).[21] In Mexico, an *ex post* analysis of improved farm management techniques (i.e., ridge planting and IPM) was shown to improve input efficiency (Traxler and Byerlee 1992a). Hence, the commodity-based approach to research, which was successful in developing input-based technologies, must be replaced by a broader systems-oriented approach to develop and adopt knowledge intensive technologies. Traxler and Byerlee (1992b) showed that returns from crop management research in Mexico are positive, which means that there is genuine potential for increased productivity through improved research in management and information skills in wheat.

Other economic and institutional mechanisms, such as extension services and price policies, must also adjust. Evenson and Rosegrant (1995) predict that extension services may make a roughly constant contribution to productivity growth until 2020. In South Asia, past extension policies that promoted technology adoption have produced only a limited number of successes, because they were directed toward promoting input use rather than input efficiency (Byerlee 1987, 1992). If extension services emphasize input efficiency over use levels, then the medium-term outlook for wheat yields would be bright even without

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[21] "High precision farming" may be defined as a form of integrated crop management that takes advantage of current and emerging technologies from university and industry research and development efforts. High precision farming is management intensive, but it adds to agricultural competitiveness while it contributes to environmental use improvements (Munson and Runge 1990).

immediate breakthroughs in breeding. Aside from problems found in extension services, the low levels of education in developing countries further constrain the adoption of more complex technologies by farmers. Institutional changes in rural education and extension must be undertaken to enable farmers to keep up with the increasing complexity of wheat production technology and so maintain productivity and sustainability.

Aside from the adjustments in extension policies, wheat pricing policy environments must also change to achieve productivity gains from efficiently utilizing inputs. In the developing world, stabilization of producer prices and subsidized input prices are the main themes of pricing policies. This approach has been appropriate for increasing input use, but may not be advisable for the transition to the input efficiency stage, nor may it be suitable in an environment where natural resource considerations become more important. The standard recommendation is to eliminate input subsidies. This provides an incentive to increase input efficiency in wheat production (Byerlee 1992). Caution, however, must be exercised in implementing such policy change, because price policy environments differ between net importing and net exporting countries, and because these policies also carry political implications. There might be inherent price distortions in some countries due to exchange rate policies, and these effects must be taken into consideration (Taylor and Phillips 1991).

In summary, better functioning markets may alleviate allocative inefficiency; better research and extension systems may decrease technical inefficiency; and greater investments in education may be crucial to reducing both allocative and technical inefficiency. However, several large unresolved issues remain relating to appropriate policy prescriptions for reducing farmer inefficiency in wheat production. At the farm level, as previously noted, more knowledge intensive technology may be difficult to apply when real wages are rising or off-farm opportunities become more attractive. In the generation of such technology, specialized crop management information that leads to greater technical efficiency is often relatively location specific. How can research and extension systems generate and diffuse this information in a cost effective manner (Pingali and Heisey 1996; Byerlee 1994)? Some answers may be provided by the successful integration of different forms of information management into ongoing wheat research programs, as exemplified by geographic information systems (GIS) and the use of crop modeling.

Sources of New Technological Breakthroughs

Improvements in production technology play a large role in increasing wheat production and yields in the long run (Rosegrant, Agcaoili-Sombilla, and Perez 1995). Ideally, in the long term, a previously untapped technology variable can increase TFP by expanding the production possibilities frontier. In other words, new technological innovations can increase the level of output using the same level of inputs used prior to the innovation. The need for new technologies as a source of productivity growth is even greater once high levels of technical efficiency have been achieved (Battese 1992). This section summarizes some potential technological breakthroughs in wheat.

Which technologies can potentially increase wheat yields in the future? It is difficult to answer this question accurately; however, past and current information can serve as the basis for reasonable conjectures. This section first addresses the two main sources of yield growth observed in the past, management and plant breeding, and then turns to the contributions made to germplasm improvement by new approaches to research, specifically wide crossing and biotechnology. Pingali and Rajaram (1997) provide a complementary perspective, organizing their discussion around wheat technology options for high potential and more marginal environments. They also discuss the effects of the liberalization of world food markets, urbanization, potentially strengthened capacity of national agricultural research systems (NARSs), advances in agricultural science, and protection of intellectual property rights on international linkages in crop improvement.

Crop Management

Technological breakthroughs in management may increase yield levels by improving the efficiency with which available purchased inputs and available resources are used. The basic tenets of high precision farming, including better varietal selection, optimal timing of fertilizer application, and conservation tillage (all of which came from breakthroughs in management and agronomic research), may be a potential source of increased productivity and yields. Agronomic research, which can lead to improved input quality, also has the potential to increase future productivity levels. Research breakthroughs in management and agronomy can provide information on how to obtain higher yields given current levels of inputs or the same level of output using lower levels of inputs.

As noted, agronomic and management research is often relatively location specific. This implies that future productivity-enhancing management changes for wheat will undoubtedly vary between environments. A very significant example: management options are likely to vary depending on the degree and timing of drought stress faced by a wheat crop over the growing season. In irrigated areas, and to a certain extent in rainfed areas with high and relatively reliable precipitation, management systems that increase efficiency for existing inputs, such as fertilizer and water, are likely to be quite important. In low rainfall, drought-stressed environments, rotations, tillage systems, and other management schemes that conserve moisture will continue to play a major role. The past history of wheat technology development suggests that management will play a relatively larger part, compared to plant breeding, in low rainfall, drought-stressed environments (Morris, Belaid, and Byerlee 1991; Hanson, Borlaug, and Anderson 1982). Diversification of enterprises is another way to stabilize incomes in marginal environments (Pingali and Rajaram 1997). Wheat management and varietal options that fit into a diversified enterprise pattern will be important in such environments.

Conventional Plant Breeding—Are Yield Gains Slowing?

As evidenced by the Green Revolution, breeding success has the potential to shift the yield frontier. Breakthroughs in plant breeding may occur through the use of conventional breeding technology, utilizing germplasm from secondary and tertiary gene pools through wide crossing, and biotechnology. In reality, these are usually closely associated activities, but for ease of exposition they are discussed separately. As will be seen, the benefits from wide crossing or biotechnology will come first through their incorporation into a conventional plant breeding program.

"Conventional breeding technology" generally refers to crossing and selection techniques that breeders use to improve observable plant traits. According to Evenson and Rosegrant (1995), conventional breeding should continue to play a significant role in increasing wheat yields over the next two decades. In this sub-section we ask whether genetic gains in yield resulting from conventional plant breeding show signs of slowing, as recently suggested, for at least some environments (e.g., Sorrells 1996). After considering some of the methodological difficulties in answering this question, we briefly present a case study of "hallmark" cultivars developed and used in the Yaqui Valley of Mexico.

What is meant by genetic gains in yield? First, a distinction must be made between genetic gains in yield in successive generations of wheat varieties and yield trends in farmers' fields. In most regions, growth in wheat yields has decreased during the past decade or longer (Tables 1 and 2). Sayre's (1996) data for the Yaqui Valley, however, suggest that slower growth in yields in farmers' fields can be consistent with continued genetic gains in varietal yields, at least over a given time period.

Second, the evidence on past genetic advances in wheat yield (summarized in the section on MVs and in Appendix A) often follows a restrictive format. Most of the estimates of genetic yield gains are expressed in percentage gains per year, implying an exponential or semi-log functional form; or as kg/ha/yr, which implies a linear functional form. The latter allows the possibility of decreasing rates of genetic gain over time, but in practice gives results very similar to those obtained from semi-log estimation. Neither functional form can capture a regime shift, such as a marked deceleration or acceleration in yield gains. Furthermore, many trials designed to evaluate genetic yield growth are treated with fungicide to avert major disease losses and planted with nets to prevent lodging. The resulting estimates of yield growth are interesting, but they may divert attention from the fact that improved resistances to disease and lodging have been important components in the progress of mean yields.

Finally, estimated growth in genetic yield potential looks only at output and not at the breeding costs required to obtain those higher yields. Slafer, Calderini, and Miralles (1996) suggest that although future genetic improvements in yield potential may be equal to those of the past 30 years or more, they will be harder to achieve and costlier than past gains.

In the Yaqui Valley of Mexico, Traxler et al. (1995) and Bell et al. (1995) have suggested that there has been a slowing in the rate of yield improvement in the post-Green Revolution period for this environment, which is typical of high-potential irrigated areas in the developing world.[22] The analysis of Traxler et al. was based on estimation of a Just-Pope production function with quadratic specification for mean yield for data from a single set of trials. Bell et al. relied on a combination of visual inspection and semi-log regression for data from a large number of trials originally conducted for a number of different purposes. Looking again at the same data, however, suggests that the apparent "slowing" of the rate of genetic yield gain in the first case results primarily from the inclusion of both tall and

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[22] Traxler et al. (1995) analyzed varieties released between 1950 and 1985; Bell et al. (1995) analyzed varieties released from 1960 through 1988.

semidwarf varieties in the same data set (thus combining the effects of the single, profound shift in yields caused by incorporation of the dwarfing characteristic with both pre- and post-dwarfing yield gains). In the second case, it is unclear how the data from different sets of trials were combined in the overall analysis.

Yields for many of the same varieties (released from 1950 to 1992) are also reported by Rajaram and van Ginkel (1996), who appear to be using n-th order statistics (highest yield) rather than means in their analysis. They apply a linear regression to their data, in other words, they assume that there has been little slowdown in the annual absolute rate of yield growth.[23] Sayre, Rajaram, and Fischer (1997) conducted a more formal analysis of a single carefully conducted yield potential trial, repeated over six years for cultivars released between 1962 and 1988, and again found no evidence of deceleration in yield growth, which increased at a rate of 0.88 % per year over the period. Although no cultivars released since 1988 out-yielded Bacanora 88, in a more limited set of trials, Sayre, Rajaram, and Fischer concluded, "it is too soon to declare that a 'yield plateau' has been reached." In yet another set of trials designed in part to monitor progress in breeding for disease resistance, with a larger, though overlapping, set of cultivars, Sayre et al. (forthcoming) estimated a lower rate of yield growth of 0.52 % per year for 1966–1988. When not protected from rust, the cultivars in this trial demonstrated a yield growth rate of 2.02 % per year, suggesting that a larger part of breeding progress over the last 25–30 years has come from maintaining yields in the face of evolving disease pathogens than from increasing yield potential *per se*.

In summary, we agree with Sayre, Rajaram, and Fischer that it is too soon to declare a leveling of yield progress in breeding for favorable, irrigated wheat environments.[24] We believe that restricting the analysis to semidwarfs, and otherwise considering the wide range of data available, one could not reject the hypothesis that the rate of growth in potential yield in the Yaqui Valley has been essentially constant for the last 30 years. Although there has been no individual breakthrough comparable to the introduction of the dwarfing characteristic, there has been steady progress in yield improvement in hallmark germplasm for favorable wheat-growing environments in the developing world in the post-Green Revolution period.

This may or may not be true for different breeding environments. There are good genetic reasons to expect continued yield progress within a single germplasm pool, yet there are also reasons to expect that "within an elite gene pool where differences between alleles are small, progress will slow and eventually level off" (Sorrells 1996; see also Rasmusson 1996). Statistical techniques used in the past may not have been sophisticated enough to detect any leveling, especially since the most recent releases and advanced lines have not been subjected to as lengthy a trial period as older cultivars.

The question implied by Slafer, Calderini, and Miralles (1996) pertains to the rate of yield increase per dollar of investment in wheat breeding. In effect, the issue is whether the

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[23] Over a long period of time, however, a linear regression would imply a slowdown in the *exponential* rate of growth.

[24] Though Rajaram and Borlaug (1997) do not confront the question of yield leveling directly, they implicitly suggest that past methods will continue to produce genetic yield advances in a variety of environments.

innovations of plant breeding are subject to diminishing, constant, or increasing returns. We believe that searching among the many potential avenues for moving yields forward (see the next sub-sections; see also Reynolds, Rajaram, and McNab 1996; Rajaram and Borlaug 1997; Pingali and Rajaram 1997) is likely to become more costly; therefore, future yield gains per dollar of expenditure could be smaller.[25] Contrary evidence is presented by Byerlee and Traxler (1996) who suggest that "the market size over which technologies are applied, rather than economies of size in producing those technologies," is a major determinant of research efficiency in crop breeding programs. In other words, for the foreseeable future, greater efficiency in the design of wheat breeding programs (number, location, questions addressed) could more than compensate for slower yield progress in dollar expended for any individual program.

Conventional Plant Breeding—Prospects for Further Progress

What are the prospects for continued increases in yield potential in wheat through conventional breeding? There are at least three physical approaches—changes in plant architecture, exploitation of heterosis, and wider genetic resource utilization (Pingali and Rajaram 1997)—that might be followed. There are also three efficiency-related avenues—exploitation of economies of scale in plant breeding, improved information management, and better use of physiological criteria—that may prove important. As enlarging the genetic resource base through wide crossing is in some sense a transition between conventional breeding and biotechnology, we discuss wide crossing in a separate sub-section. The other options are outlined here.

Wheat plant architecture has continued to evolve since the introduction of semidwarf wheat varieties. In addition to dwarfing genes, the incorporation of photoperiod insensitivity and the exploitation of spring by winter wheat crosses have contributed towards more efficient plant types (Pingali and Rajaram 1997). CIMMYT breeders have also developed an ideotype, targeted to irrigated and high-rainfall environments, with robust stem, long head, multiple spikelets and florets, a large leaf area, and broad leaves. At this time, however, the heads remain largely sterile, most of the grains are shriveled, and the plants tend to be rust-susceptible. Future plans call for crossing these materials with good advanced lines from the CIMMYT breeding program, the objective being the creation of a slightly smaller spike and completely restored fertility. Incorporation of this ideotype into the development of hybrid wheat may also enhance grain filling (Rajaram and Borlaug 1997).

Another breeding option for increasing wheat yields is the exploitation of heterosis. Research interest in hybrid wheat was spurred by the development of successful maize hybrids and then slowed in the USA by the spread of semidwarfs as a yield-increasing alternative. Waves of optimism and pessimism also were related to the technical advances that permitted the development of hybrid wheat. These included: the discovery of cytoplasmic male sterility/restoration factor systems in species closely related to cultivated wheat in Japan and the USA in the 1950s and 1960s; the discovery of nuclear male sterility in wheat in Italy in the late 1960s; and the development of gametocide, or pollen suppresor, technology in the USA in the

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[25] For an interesting discussion of the concepts and possible mathematics that might help to resolve this question, see Weitzman (1996).

early 1970s. Large seed companies, such as Pioneer and DeKalb, entered and left the hybrid wheat seed market. Cargill left the US market in 1990, but continued in Australia and Argentina. Monsanto (which owns a pollen sterilization technology) still maintains a hybrid wheat program (Knudson and Ruttan 1988; Pickett and Galwey 1997).

Perhaps because of the market success of hybridization in rice (another self-pollinated crop) in China (Lin 1991), interest in hybrid wheat is again strong.[26], [27] The ultimate economic success of hybrid wheat will depend on many of the factors that determined the success of hybrid maize. On the demand side, these include the yield advantage of hybrids, the seed rate, the extra return required to compensate the farmer for the cost of capital, learning costs, risk, and, of course, the seed price—which is determined by both supply and demand. On the supply side, important factors include the costs of seed production and research innovation (the elements most directly determined by technological factors), the total size and composition of the potential market, the organization of the seed industry, and the economic or political importance of wheat in a given economy (Heisey et al. 1998). Many of these demand side factors are similar to those identified by Jordaan (1996).

We used data presented in Knudson and Ruttan (1988) and mid-1980s US wheat prices, along with an assumed minimum acceptable marginal rate of return of 100% (CIMMYT 1988)[28] to calculate the economic viability of hybrid wheat in the USA in the mid-1980s. To increase the likelihood of wide adoption of hybrids,[29] the price of hybrid wheat seed would have to have been 8.4% lower, or the yield advantage over the best alternative conventional variety would have to have been at least 15.4%, rather than the 13.3% it actually was in Kansas (the state where mid-1980s hybrids performed best). To date, it does not appear that hybrid wheat has been widely adopted in Kansas (Barkley and Porter 1996).[30]

At present, the best prospects for hybrid wheat appear to be in the high-yielding environments of Western Europe or for irrigated production in developing countries. Alternatively, new management methods that significantly reduce seeding rates could improve the prospects for hybrid wheat. In South Africa, for example, where wheat is often grown under stress conditions and yields are relatively low, prospects for hybrid wheat may be reasonable because of low seeding rates, relatively high wheat prices, and a commercialized wheat farming sector.

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[26] Because rice is a diploid species, parental development for hybrid production in rice may be somewhat easier than in bread (hexaploid) or durum (tetraploid) wheats.

[27] Research on hybrid wheat in recent years has taken place in Western Europe, where hybrids have been following the path to release in France and the UK (Pickett and Galwey 1997); and in the USA, Australia, South Africa, Argentina, Russia, and Kazakhstan. China and India have recently stepped up hybrid wheat research, and CIMMYT re-initiated its hybrid wheat program in 1996 (CIMMYT 1997).

[28] Private seed companies often operate on the assumption that even greater marginal returns are needed to induce adoption of a new technology (McMullen 1987; C. Krull, personal communication).

[29] These margins would be wider if it were assumed that the true alternative to hybrid wheat for farmers was usually retained seed, rather than commercial seed of a conventional variety.

[30] In 1997, for the USA as a whole, perhaps 200,000 ha, slightly under 1% of total wheat area, were planted to hybrid wheat (M. van Ginkel, personal communication).

Generally, the technical advances most likely to improve the feasibility of hybrid wheat are methods of improving seed set in female plants, which will reduce hybrid seed prices, and a much better knowledge of heterotic groupings in wheat, which should increase the yield advantages of hybrids over conventional cultivars (Jordaan 1996; Lucken 1987). Pickett and Galwey (1997) also stress male sterility, seed production, and hybrid performance, but are more pessimistic about widespread commercialization of hybrid wheat. They argue that scientific advances, including progress in biotechnology, may allow a reduction of costs in hybrid seed production systems; however, they maintain that although hybrids may continue to show some yield advantages over conventional wheat cultivars, scientific progress will also raise yields of pure-line cultivars to the point that hybrids will not have a clear economic advantage.

This paper hypothesizes that genetic improvement will play a less important role relative to management research in more marginal environments. Nonetheless, there is considerable evidence that improved wheat cultivars often perform better than their predecessors under many stress conditions (e.g., Pfeiffer and Braun 1989; Sayre 1996; Jordaan 1996; Rajaram and Borlaug 1997). For contrary evidence under very dry conditions, see Blum (1996). A pertinent question is whether yield gains achieved under more optimum management conditions also lead to yield advances under stress. This may depend on the nature of the stress, with spillovers from more favorable to less favorable environments likely for stresses such as drought, heat, lack of macronutrients, waterlogging, and moderate salinity. Stresses such as mineral toxicity, micronutrient deficiency, nematodes, soil-borne pathogens, and weeds may require more direct confrontation (Reynolds, Rajaram, and McNab 1996).

More generally, efficiency in wheat breeding will depend on continued exploitation of economies of scale at the level of breeding program design, as suggested by Byerlee and Traxler (1996). For example, the present international wheat breeding system employed for developing countries integrates a centralized breeding program with regionally and locally focused programs. The former has wide access to germplasm and information and makes and evaluates a large number of crosses in every cycle. The latter can make crosses and select germplasm better adapted to local conditions. Continuing such a system, or even improving its efficiency, should assist in further gains in yield potential (Maredia and Byerlee, 1999; Pingali and Traxler 1997; Rajaram and van Ginkel 1996). However, restrictions on the free flow of germplasm, for example, restraints coming through the passage of certain types of intellectual property rights (IPR) legislation, could compromise the ability of this system to produce wheat varieties with improved yields (Kronstad 1996; Rejesus, Smale, and van Ginkel 1996; Pingali and Rajaram 1997).

Another option for greater efficiency would be improved information management within international breeding systems. The nascent International Crop Information System (ICIS) potentially could: assist in the management of complex experimental designs; store more complete environmental characterizations of trials; enable faster information turnaround to scientists making decisions on the basis of widely distributed trials; manage genetic data for lines and cultivars, including molecular information; and convert data into formats suitable for crop simulation modeling or GIS analysis (Fox, Skovmand, and White 1996; Sorrells 1996).

A third route to enhance efficiency in conventional breeding is to better incorporate an understanding of plant physiology into breeding programs. For example, plant physiologists and other scientists have identified a number of characteristics associated with the increase in yield potential in spring bread wheat germplasm originating from CIMMYT (e.g., Waddington et al. 1986; Rees et al. 1993; Reynolds et al. 1994; Sayre, Acevedo, and Austin 1995; Fischer 1996a; Sayre, Rajaram, and Fischer 1997; Fischer et al. 1996). These include higher stomatal conductance, higher maximum photosynthetic rate, cooler canopies, and a less competitive plant type. To date, however, none of the physiological traits shown to be associated with yield potential have been used as selection criteria (Rajaram and van Ginkel 1996), pending the study of these traits in an ongoing breeding program.

Both breeders and physiologists expect crop physiology to make a greater contribution to plant breeding during the next 20 years. This is more likely to happen if physiological research works with relevant genetic populations and contributes to identifying genes underlying physiological differences, it is integrated with an active breeding program, and it avoids a narrow focus. Beyond identifying traits for indirect selection criteria, physiology can also contribute to the identification of selection criteria and traits for focused introgression programs, and to the selection of better environments in which to conduct selection trials (Jackson et al. 1996).

Enlarging the Genetic Resource Base through Wide Crossing

Wide crossing is a technique whereby two plants that usually do not hybridize by means of conventional breeding are made to hybridize, such as crosses from two genera (e.g., wheat and rye) or crosses from a cultivated crop and its wild relative (e.g., bread wheat and the *Triticum* grass species). In a sense, wide crossing is an intermediate technology between conventional breeding and more recently developed biotechnology techniques. One application has already been noted: the development of cytoplasmic male sterility-restoration factor systems for the production of wheat hybrids. As with other biotechnologies, wide crossing also bears on the questions of economies of scale and international research coordination considered above, with respect to conventional breeding. Because of long delays in payoffs encountered with this approach, wide crossing is often most feasible for large, centralized public sector programs.[31]

Wheats descended from wide crosses are expected to provide improved resistance to diseases and other biotic stresses, and tolerance to abiotic stresses in the intermediate term (Byerlee 1994; CIMMYT 1995; Evenson and Rosegrant 1995). Resistance has been found or is being sought for Karnal bunt, spot blotch, *Septoria tritici*, and scab. Other biotic stresses under investigation include barley yellow dwarf virus and Russian wheat aphid. Work on abiotic stresses has focused on tolerance to salt, aluminum, and drought. Another important aspect of wide cross research has been its integration with other techniques, including: polyhaploid production, which reduces the number of generations necessary to fix the homozygosity of wheat; tissue culture, which will extend the range of wide cross possibilities; and methods of confirming alien introgressions through biochemical or molecular markers (Mujeeb-Kazi and Hettel 1995).

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[31] For data on the actual use of wild relatives by wheat breeding programs worldwide, see Rejesus, Smale, and van Ginkel (1996).

It appears that the greatest contribution of wide crossing in the foreseeable future will be to increase yield stability rather than yield potential *per se*. In the long run, wide crossing could provide higher rates of photosynthesis, but it is unclear to what extent it might enhance yield potential (Evans 1993). Theoretically, enlarging the genetic base available for wheat improvement should create more variability for complex quantitative traits such as yield. Positive alleles, however, are likely to be present in low frequencies, making them hard to identify and difficult to separate from many negative alleles. In the future, the use of molecular markers, could help "facilitate the interspecific transfer of desirable quantitative alleles from the wild species into cultivated genotypes and . . . selectively retain desirable alleles from the elite parent" (Sorrells 1996), thus enhancing the possibility of increasing yield potential through the use of exotic sources.

Contributions from Biotechnology

Biotechnology, recent general surveys suggest, is the technology most likely to provide the largest, longer-term productivity gains for wheat (Evans 1987; Riley 1992; Byerlee 1994; Evenson and Rosegrant 1995). Biotechnology encompasses a continuum of related technologies usually aimed at accomplishing what normal breeding cannot efficiently or fully undertake, such as breeding for plant traits that are difficult to observe and gene transfer. Some of the likely linkages between recently developed biotechnologies and wide crossing were discussed earlier. In the long term, several other biotechnologies can potentially help attain breeding breakthroughs in wheat; these include marker-assisted selection and diagnostics, doubled haploid techniques, and gene transfer technology or genetic engineering.

Marker-assisted selection could reduce the cost of developing new varieties by employing molecular markers and improved diagnostics for more precise selection of plants that carry genes for desirable traits—or rejection of plants that carry unwanted genes (Sorrells and Tanksley 1992; Byerlee 1994; Snape 1996). The use of molecular techniques for genetic mapping, in conjunction with conventional breeding, may provide a more efficient transfer of quantitative characteristics into new germplasm, thereby reducing costs. For plant characteristics that require more time and resources to observe, such as aluminum tolerance, transfer of traits should be especially efficient using molecular mapping technology. Although there is no firm empirical evidence of the cost advantage of using this technique, a reduction in the time required to develop varieties provides substantial potential payoffs owing to the decreased lag between the time when research costs are incurred and when benefits are received by farmers (Brennan 1989).

The use of molecular markers in wheat has been limited by several factors. Markers exist for many important genes that control the development of the wheat plant, for example vernalization, photoperiod, and earliness *per se*, but in general, markers have been too loosely linked to important genetic regions to serve as effective diagnostic tools. One constraint is the ploidy level of wheat—the number of different genomes, or chromosome groups, that constitute wheat's genetic material. Another is the low degree of polymorphism, or variability of particular alleles, in elite wheat germplasm. Solutions to these problems may eventually be derived from recent findings of similar genetic organization across the different genomes of bread or durum wheat and of homologous genetic patterns across all the cereals. Genetic findings in other cereal species may prove quite useful in understanding the location and function of important genes in wheat. A major strategic question may involve the relative payoffs to focusing first on developing ever more precise markers for selected genes, versus developing a comprehensive genetic map of the entire wheat genome (Snape 1996; Sorrells 1996).

The use of doubled haploid systems can shorten the time between a cross and the achievement of genetic stability (homozygosity). Several European commercial wheat breeding companies currently use this process, and lines produced are now entering national trials. The technology is more expensive than conventional breeding and only a limited number of crosses can be managed, meaning a new technological breakthrough will be necessary before it can be widely applied (Snape 1996).

The biotechnology most popularly known (and feared) is the process of transferring genes from unrelated species to produce transgenic wheat and other plants. For example, if a gene or gene combination can be found to increase photosynthetic activity through improvements in the rate-limiting enzyme called rubisco, yield potential may substantially increase (Evans 1986). The contributions of genetically transformed wheat crops, however, will probably not be seen within the next two decades (Larkin 1990; Persley and Peacock 1990; Dalrymple and Srivastava 1994; *The Economist* 1995). Genetic transformation techniques for wheat are in their infancy, and "formidable challenges remain in terms of understanding gene expression, stability, and durability." Some realistic targets presently available for the transformation of wheat include fungal, virus, insect, and herbicide resistance; quality characteristics; and sterility systems useful in the development of hybrid wheat (Snape 1996).

There are some notable economic factors that may affect potential gains from biotechnologies. First, the public investment needed to undertake effective biotechnology research is considerably more than that required for conventional breeding and management research. High-income countries and international agricultural research centers (IARCs) such as CIMMYT are the best positioned public entities to feasibly undertake biotechnology research on wheat (Barker 1990). Although the scientific capacity of NARSs in developing countries is greater today than at any previous time (Byerlee and Traxler 1995), collaborative arrangements with IARCs and high-income countries will remain an important complement for developing country NARSs, enabling them to share the benefits of biotechnology.

Wheat also has not received the degree of private sector biotechnology research seen in other crops (Larkin 1990).The low private sector role in wheat puts further pressure on public sector institutions (IARCs and NARSs) to increase biotechnology research initiatives. Given the high cost, long-term investment, and high technical capacity required for biotechnology research, developing countries need to make strategic decisions on capacity development (e.g., how much to develop in-house, how much to import, and what level of regional or other cooperation to enter) to gain the benefits of biotechnology in the future.

Summary and Conclusions

Given overall population growth over the next 30 years, together with a projected increase in per capita demand for wheat in the developing countries, wheat production will have to grow to meet increasing demand.[32] Although there will be slight increases in the area planted to wheat, most of the requisite production increase must come from higher yields. The required yield increases are below recent historical rates of growth. However, the proposed sources for further yield progress in wheat are more diffuse than they were 30 or 40 years ago, when the model of intensive irrigated agriculture in countries such as Japan pointed to the combination of high-yielding varieties that shifted out the yield frontier and were more input responsive, with greater use of inputs such as fertilizer and water. For the foreseeable future, costs of achieving a given rate of yield growth may be higher than they were in the Green Revolution period.

Continued investment in wheat research is crucial. We believe that the “pessimistic” or Malthusian analysts who see disaster looming in recent lower rates of yield growth in cereals are incorrect. The continued long-term decline in the real price of wheat suggests that demand forces, not simply supply constraints, have reduced the overall growth rate of wheat production. Periods in which the real world wheat price has increased sharply are also usually explained as much by market conditions as by sharp reductions in supply caused by variability in nature. At the same time, “market-oriented” or “cornucopian” writers who believe that simply “getting prices right” or “removing constraints on farmers” will assure the requisite wheat supplies into the indefinite future are also incomplete in their analyses. Although farmers and, if the induced innovation hypothesis (Hayami and Ruttan 1985) is correct, researchers are indeed price responsive, without investments in research, growth in wheat yields will eventually taper off. Indeed, with no research at all, changes in environmental conditions, such as the evolution of wheat diseases, would eventually lead to declining yields. This understanding lies behind the “middle-of-the-road” scenarios, such as those of IFPRI (Rosegrant, Agcaoili-Sombilla, and Perez 1995) and FAO (Alexandratos 1995), that suggest: continued but slower declines in the real price of wheat over the next several decades, with maintenance of the current level of investment in agricultural research; an increase in the real price of wheat, with further cutbacks in research support; and greater short-term variability in wheat prices, in whatever scenario, because of greater reliance on market forces in the world wheat market.

What are the sources of future improvements in wheat yields and output? This paper has presented a general framework for analyzing technological change that includes both shifts in the yield frontier (such as occurred with the diffusion of seed-fertilizer technology in wheat) and improvements in allocative and technical efficiency (occurring as farmer learning, improvements in market efficiency and infrastructure, and management research move farmers closer to the yield frontier).

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[32] Actual percentages by which wheat production will have to grow cannot be directly inferred solely from the population growth rate and the growth of per capita demand in developing countries. It is also necessary to know base population proportions for developing and industrialized countries, how these proportions shift over time, and base per capita consumption in both groups.

Increases in wheat yield or output associated with large increases in fertilizer use or irrigated wheat area are unlikely to have the same relative importance that they did during the Green Revolution and First Post-Green Revolution Phases. In parts of some developing countries, however, some further input intensification is likely. Continued progress on the wheat plant's efficient conversion of nutrients into grain could also spur increased fertilizer use.

A more important source of increased yields could be greater efficiency of input use. What are the prospects for higher wheat yields and increased productivity from this source? There are several types of studies that bear on this issue, but they are not completely conclusive. First, unpublished data from advanced Green Revolution areas such as the Indian Punjab show that the gap between wheat yields on farmers' fields and yields on experiment stations is narrowing over time (Byerlee 1992). This could imply simply that farmers are using more inputs or that they are growing wheat more efficiently, or both. Second, TFP studies for the Indian states of Punjab and Haryana (Sidhu and Byerlee 1992; Murgai 1997) also suggest, but do not prove, that farmer efficiency may have stimulated productivity growth in the Post-Green Revolution Phase, but that this result varies substantially from district to district. Alternatively, nearly all of the studies of static efficiency in wheat production reviewed herein show substantial farmer inefficiencies.

Studies that combine time-series data with traditional efficiency analysis could help resolve some issues that bear on whether there is a large scope for increasing wheat yields through increased efficiency. We have argued that indeed this is likely to be a major source of increased wheat productivity, provided that problems of location specificity in appropriate crop management research can be solved with better information management; extension services are better implemented; complementary investments are made in farmer education; and pricing policies are shifted to better reflect social opportunity costs. The general equilibrium effects of these policies, however, are still uncertain, as they depend on the real farm wage rate and off-farm employment opportunities. The role of crop management research and improved farmer efficiency in raising wheat yields seems highly deserving of further study.

Other substantial gains can be made if there are further scientific advances in wheat breeding. Continuous adoption of newer and better MVs is needed to further improve productivity in wheat cropping systems. Although there is ample evidence, it is not widely appreciated that genetic gains in wheat *since* the original incorporation of dwarfing genes have been a substantial source of yield progress or that these benefits have in many cases spilled over into more marginal environments.

This yield progress may continue both through conventional breeding (including, in some areas, hybrid wheat) and through the use of marker-assisted selection and doubled haploid techniques that accelerate the breeding cycle. Wide crossing, marker-assisted selection, and genetic transformation also have the potential in the intermediate term to enhance stress resistance in wheat, making yields less variable in both favorable and more marginal environments. It is more difficult to see when these contributions from biotechnology will have direct impact on yield under optimal conditions, a complex trait governed by many genes.

In conclusion, there are many technological opportunities for increasing wheat yields over the next decades. There is, however, no single evident path to those increased yields. Strategies will be more location specific and dependent both on continued research investment and appropriate policies. Yield gains are also likely to be costlier to achieve than during the past 30 years. On the positive side, many of the sources of yield growth surveyed in this paper show promise of raising productivity in wheat farming, not simply boosting output through the increased use of inputs such as fertilizer or water. Provided that the world wheat research community remains integrated[33] while developing countries make strategic decisions on research capacity development, wheat supply should meet projected demand well into the 21st century. Whether this results in improved welfare of the poor and reduced levels of environmental stress depends as much on appropriate policies as it does on technological change.

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[33] As noted above, Pingali and Rajaram (1997) outline a cautiously optimistic prospectus that the international wheat research enterprise will remain integrated.

Appendix A

Evidence on Rates of Genetic Gain in Bread Wheat

The following table presents an incomplete summary of studies that report genetic rates of gain in bread wheat. Much of the information for lower latitude, spring bread wheat was first summarized by Byerlee and Moya (1993). Most of the studies are based on trial data, although Silvey (1978) uses a model to decompose actual wheat yields in the UK. Many trials, particularly those conducted in irrigated spring wheat environments, used fungicide to protect against disease losses, and netting to eliminate the effect of lodging.

Environment/location	Period	Rate of gain (%/yr)	Data source
Spring Habit Wheat			
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)
	1962–88 [a]	0.9	Sayre, Rajaram, and Fischer (1997)
Nepal	1978–88 [a]	1.3	Morris, Dubin, and Pokhrel (1992)
India	1911–54	0.6	Kulshrestha and Jain (1982)
	1967–79	1.2	
Northwest India	1966–90 [a]	1.0	Jain and Byerlee (1999)
Pakistan	1965–82 [a]	0.8	Byerlee (1993)
Zimbabwe	1967–85 [a]	1.0	Mashiringwani (1987)
Hot (irrigated)			
Sudan	1967–87	0.9	Byerlee and Moya (1993)
Rainfed			
Argentina	1912–80	0.4	Slafer and Andrade (1989)
	1966–89	1.9	Byerlee and Moya (1993)
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 (1987)
Western Australia (low rainfall)	1884–82	0.4	Perry and D'Antuono (1989)
Central India	1965–90	0.0	Jain and Byerlee (1999)
Acid Soils (rainfed)			
Rio Grande do Sul, Brazil	1976–89	3.2	Byerlee and Moya (1993)
Parana, Brazil	1969–89	2.2	Byerlee and Moya (1993)
High Latitude (rainfed)			
North Dakota, USA	1934–69	0.3	Feyerherm and Paulsen (1981)
	1970–78	2.4	Feyerherm, Paulsen, and Sebaugh (1984)
Western Canada	1893–1980	0.0	Hucl and Baker (1987)
	1926–80	0.4	
	1934–80	0.2	
Western Canada	1900–90	0.2	McCaig and DePauw (1995)

Winter Habit Wheat			
Kansas, USA (hard red winter)	1932–69	0.6	Feyerherm and Paulsen (1981)
	1971–77	0.8	Feyerherm, Paulsen, and Sebaugh (1984)
	1874–1970	0.4	Cox et al. (1988)
	1976–87	1.2	
Oklahoma/Texas, USA (hard red winter)	1932–74	0.8	Feyerherm and Paulsen (1981) Feyerherm, Paulsen, and Sebaugh (1984)
US corn belt winter (soft/hard)	1934–67	0.4	Feyerherm and Paulsen (1981)
	1968–76	1.7	Feyerherm, Paulsen, and Sebaugh (1984)
US winter (various regional performance nurseries)	1958–78	0.7-1.4	Schmidt (1984)
UK (low fertility)	1908–78	0.5	Austin et al. (1980)
UK (high fertility)	1908–78	0.4	Austin et al. (1980)
UK	1947–77	1.5	Silvey (1978)
Sweden	1900–76	0.2	Ledent and Stoy (1988)

[a] Semidwarfs only.

[b] Unpublished data.

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