Chapter 6

Empirical Evidence of Gains in Yields and Other Characteristics

In this chapter we review empirical evidence of tangible outcomes of CIMMYT and NARS wheat breeding programs, with additional relevant evidence from wheat breeding programs in other institutions. We begin by assessing empirical experimental evidence of gains in wheat yield and wheat yield potential. This evaluation is followed by a brief summary of selected components of gains in wheat yield. The final section of the chapter reviews actual wheat yields in developing countries and asks to what extent experimental gains have translated into gains in farmers' fields.

Considerable evidence suggests that wheat yields and wheat yield potential both increased from the introduction of semidwarf wheat varieties at the beginning of the Green Revolution to the late 1990s. At the same time, gains in worldwide industry wheat yields have decelerated over the past 15 years or so. As a result, direct use of experimental yield gains to model industry yield gains is less justifiable today than was in the past. In order to refine our understanding of how gains made by wheat improvement scientists are being transferred to developing country wheat fields, a greater effort will be needed to collect and interpret data, classified according to major wheat-growing environments in the developing world, rather than political boundaries. Nonetheless, advances made by wheat breeders in yield potential, disease resistance and other characteristics demonstrate that wheat supply is considerably greater than it would have been without an international breeding effort. Furthermore, wheat supply with only NARSs' breeding efforts would have been greater than what it would have been with no wheat breeding at all.

Experimental Gains in Wheat Yields

Crop scientists often distinguish between gains in yield potential and gains in yield. Yield potential has been defined as "the yield of a cultivar when grown in environments to which it is adapted; with nutrients and water non-limiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled" (Evans 1993). In the previous chapter, we outlined conceptual approaches to measuring gains in yield and yield potential. But as Evans and Fischer (1999) noted, it is not easy to verify that nutrients and water are non-limiting and that stresses are effectively controlled, because of the possibility of emerging or unrecognized stresses and side-effects of control. In many experimental studies of the type summarized below, attempts were made to supply nutrients and water at non-limiting levels. In some trials, efforts were also made to control for the effects of foliar diseases and lodging.[28]

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[28] Lodging control may be particularly relevant when comparing semidwarf and tall varieties in the same trial because one major advantage of semidwarf varieties has been their resistance to lodging.

Scientific Reviews of Gains in Wheat Yield Potential and Wheat Yield

The recent deceleration in the growth of world wheat yields has led some observers to infer that breeding gains in wheat yield potential may also be slowing. However, a major scientific review of yield gains in several different crops concludes that the best available data support the view that wheat yield potential has continued to increase since the Green Revolution (Evans and Fischer 1999). Reynolds, Rajaram, and Sayre (1999) focus more specifically on irrigated wheat and some factors responsible for this gain in yield potential. They also argue that there was no observable slowing in the rate of growth in wheat yield potential up through the mid-1990s.

Genetic Gains in Yield from Successive Release of New Wheat Varieties

Byerlee and Moya (1993) summarized data on genetic gains in yield resulting from the release of new wheat varieties over time. Many of these data were obtained from trials in which varieties with different years of release were grown under the same environment and management. Rejesus, Heisey, and Smale (1999) reviewed the results of other trials. In Table 6.1, we combine these summaries and add the results of other trials. A few results are presented from industrialized countries, particularly for Mediterranean-type (winter rainfall) environments such as drought spring wheat, high latitude spring wheat, and winter wheat. These results are included to give some idea of yield gains in environments that also exist in some developing countries.

Though yield gains are used here because they give clear evidence of impacts of past research, it is important to bear in mind that yield gains expressed in percentage terms may not be independent from base yield levels, and the time periods for which yield gains or base yields are measured may also be significant. Yield gains over time as reported in Table 6.1 are estimated using

Table 6.1. Evidence on rates of genetic gain in bread wheat in developing and industrialized countries, 1962-1997.

Developing Countries			
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)
	1988-96[a]	0.8	H.J. Dubin, CIMMYT[b,c]
Nepal	1978-88	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)
	1985-95[a]	0.9	H.J. Dubin, CIMMYT[b,c]
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			
Ethiopia	1967-94	1.2-1.7	Amsal et al. (1996)
Uruguay	1966-95[a]	1.4 (high fertility)	M. Kohli, CIMMYT[b]
	1966-95[b]	0.9 (low fertility)	M. Kohli, CIMMYT[b]
Paraná, Brazil (non-acid)	1978-94	0.9	M. Kohli, CIMMYT[b]
Argentina	1912-80	0.4	Slafer and Andrade (1989)
	1966-89	1.9	Byerlee and Moya (1993)
	1971-89[a]	3.6 (unprotected)	M. Kohli, CIMMYT[b]
	1971-89[a]	2.1 (unprotected)	M. Kohli, CIMMYT[b]
	1988-97[a]	3.7	M. Kohli, CIMMYT[b]
Paraguay	1972-90	1.3	M. Kohli, CIMMYT[b]
	1979-92[a]	1.6	M. Kohli, CIMMYT[b]
Bolivia	1986-96[a]	1.0	M. Kohli, CIMMYT[b]
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)
Paraná, Brazil	1969-89	2.2	Byerlee and Moya (1993)
	1970-96[a]	0.2 (ns)	M. Kohli, CIMMYT[b]
Facultative / winter (rainfed)			
South Africa	1930-90	1.4	Van Lill and Purchase (1995)

[a] Semidwarfs only.
[b] Unpublished data.
[c] Two-variety comparison only.

semi-logarithmic regression (gains are expressed as the average percentage change per year). An alternative method often used by crop scientists to measure genetic gains is linear regression (gains are expressed as the increase in kilograms per hectare per year).

For a number of reasons, yield gains are imperfect measures of research performance. On the output side, yield data may not reflect differences in market classes and value. On the input side, yield data across different ecologies usually represent different levels of input use and thus different levels of production costs. Yield gains may be lower when calculated over longer periods, making comparisons across studies problematic. Furthermore, for both types of yield gains, individual studies may happen to straddle a quantum leap in yield potential, such as the one that occurred following the introduction of semidwarf wheat, whereas others may refer only to periods before or after large shifts in yield potential.

Table 6.1. (continued) Evidence on rates of genetic gain in bread wheat in developing and industrialized countries, 1962-1997.

Industrialized Countries			
Environment / location	**Period**	**Rate of gain (% / yr)**	**Data source**
Spring habit wheat			
Rainfed			
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	1884-1982	0.4 (low rainfall)	Perry and D'Antuono (1989)
High latitude (rainfed)			
North Dakota, U.S.	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 wheat			
Rainfed			
Kansas (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 (hard red winter)	1932-74	0.8	Feyerherm and Paulsen (1981) Feyerherm, Paulsen, and Sebaugh (1984)
U.S. Corn Belt winter (soft / hard)	1934-67	0.4	Feyerherm and Paulsen (1981)
	1968-76	1.7	Feyerherm, Paulsen, and Sebaugh (1984)
U.S. winter (various regional performance nurseries)	1958-78	0.7-1.4	Schmidt (1984)
U.K.	1908-78	0.5 (low fertility)	Austin et al. (1980)
U.K.	1908-78	0.4 (high fertility)	Austin et al. (1980)
U.K.	1947-77	1.5	Silvey (1978)
Sweden	1900-76	0.2	Ledent and Stoy (1988)

Nearly all of the studies whose results are reported in Table 6.1 showed significant gains in yield potential even when the data were restricted to MVs, giving further credence to the argument that MV turnover in wheat as well initial MV adoption can lead to significant yield gains. Although it is not always possible to characterize the environments in which these trials were conducted, about 30 trials were reported from irrigated environments or environments with more reliable rainfall, and about 15 were reported from drier, less reliable environments. It is important to remember that these environments differ by factors other than rainfall and that previously mentioned complications such as the time period covered by the trials also hamper comparisons. Nonetheless, the median yield gain in better-watered environments was about 1% per year; the median gain in drier environments was about 0.4% per year.

Wheat breeders clearly have been successful in raising wheat yields in a wide variety of different environments and time periods. The most rapid increases in yields have often been associated with the switch to semidwarf varieties. However, in some locations genetic gains in yield were observed before semidwarf cultivars were widely used. Furthermore, in nearly all cases breeders have continued to increase wheat yields in semidwarf varieties. In some cases, progress in raising yields may have been slowed because of emphasis on other varietal characteristics, such as grain quality.

Results from International Yield Trials

International yield trials—trials of wheat varieties grown in many locations around the world in a number of seasons—can also provide perspective on yield gains resulting from plant breeding. Using data from CIMMYT's International Spring Wheat Yield Nursery (ISWYN) from 1980 to 1988, Maredia, Ward, and Byerlee (1999) considered spillover potential across breeding programs. They showed that across most major spring wheat growing environments in the developing world, yields of CIMMYT crosses were greater than or equal to yields of locally bred varieties originating from within each environment. Weighting by relative areas in the different environments, and adjusting trial yields to yields under farmers' conditions, the yield advantages averaged about 200 kg/ha in farmers' fields. Note that this is a yield advantage of CIMMYT crosses over other improved wheat varieties, some of which may also have some CIMMYT content.

Recently Lantican, Pingali, and Rajaram (2001) looked at yield gains both in the ISWYN from 1964 to 1995 and in the CIMMYT Elite Spring Wheat Yield Trial (ESWYT) from 1979 to 1999. In contrast to Maredia, Ward, and Byerlee, their analysis focused on yield gains over time rather than spillover potential, although Lantican, Pingali, and Rajaram's work also demonstrated the importance of spillovers across spring wheat growing environments in the developing world. Indeed, one of their most important objectives was to compare and contrast yield gains through time achieved in different environments. In another interesting contrast with the trial-based analysis reported in Table 6.1, Lantican, Pingali, and Rajaram used extreme values, basing their regressions on the top three yields in each location.

In the ISWYN, yield gains for four types of environment—irrigated, high rainfall, drought prone, and high temperature—ranged between 1.22% and 1.72% annually between 1964 and 1978. Since base yields were higher in irrigated and high rainfall environments, gains expressed in absolute terms (kilograms per hectare per year) were less than half in drought-prone and high temperature environments than they were in irrigated and high rainfall environments. From 1979 to 1995, yield gains in irrigated and high rainfall environments were about the same in percentage terms and in absolute terms as they had been in the earlier period. In less favorable environments, percentage yield gains increased between 2.53% and 2.75% annually, and gains in kilograms per hectare per year, although still lower, were now more similar across all four environments (Table 6.2). It should be noted that despite the increase in rates of yield growth in marginal environments relative to favored environments in the latter period, these results still imply maximum trial yields in dry or hot environments of about 3.5-4 t/ha at the end of the sample period, compared with yields of about 7-8 t/ha in favorable environments at the end of the sample period.

In the ESWYT trials, yield gains expressed both in percentage terms and in absolute terms were greatest in dry environments (Table 6.3). Despite the high rates of growth in these environments, the maximum experimental ESWYT yields were

Table 6.2. Trends in developing country wheat yield potential by environment, International Spring Wheat Yield Nursery (ISWYN), 1964-95.

		Environment			
Period		Irrigated (ME 1)	High Rainfall (ME 2)	Dry (ME 4)	Hot (ME 5)
1964-78	Growth rate (%/yr)	1.22	1.72	1.54	1.41
	Growth (kg/yr)	71.6	81.5	32.4	34.9
1979-95	Growth rate (%/yr)	1.32	1.71	2.75	2.53
	Growth (kg/yr)	84.6	92.8	70.5	72.3

Source: Lantican, Pingali, and Rajaram 2001.

only around 3.5 t/ha by the late 1990s, compared with yields of 6-7 t/ha in high rainfall and irrigated environments. Yields in hot environments were even lower than those in dry environments at the end of the 1990s.

Much of the yield gains in hot and dry environments, however, represent spillovers from wheat research for irrigated environments. Moving from experimental to farmers' field data, Lantican, Pingali, and Rajaram (2001) show that in both 1990 and 1997 over 60% of the wheat area in dry and hot environments (excluding the area planted to landraces) was planted to varieties with one parent from an irrigated environment, and another one-eighth to one-sixth was planted to varieties for which both parents were varieties originating in irrigated environments. Only one-fifth to one-quarter of the area was planted to varieties directly targeted to either dry or hot environments.[29]

Components of Wheat Yield Gains

Improved yield performance has been associated with higher yield potential. In a survey of more than 70 wheat breeders in developing countries, Rejesus, Smale, and van Ginkel (1996) found that yield potential was one major reason for the use of CIMMYT wheats by these programs. Superior stress resistance is another important characteristic associated with CIMMYT wheat. Smale et al. (2001) summarize much of the known research about components of yield gains related to stress resistance.

Table 6.3. Trends in developing country wheat yield potential by environment, Elite Spring Wheat Yield Trial (ESWYT), 1979-99.

	Environment			
	Irrigated (ME 1)	High Rainfall (ME 2)	Dry (ME 4)	Hot (ME 5)
Growth rate (%/year)	0.82	1.16	3.48	2.10
Growth (kg/year)	53.5	62.5	87.7	46.1

Source: Lantican, Pingali, and Rajaram 2001.

A major goal of most wheat breeding programs is to develop resistance to diseases, particularly rusts. Over the period 1966-88, much of the increase in yields in CIMMYT-derived cultivars may have been due to superior leaf rust resistance, rather than increases in physiological yield potential (see Figure 6.1, taken from Sayre et al. 1998). Respondents to the survey of breeding programs indicated that disease resistance was another major reason for incorporating CIMMYT germplasm (Rejesus, Smale, and van Ginkel 1996). Improving race-nonspecific rust resistance has been a major strategy in the breeding effort to confer superior rust tolerance (Smale et al 1998; Marasas, Smale, and Singh, forthcoming).

Over time, successive generations of CIMMYT wheat have shown steady improvement in their ability to respond to abiotic stress. Although high yielding wheat is often thought to require more nitrogen, over time CIMMYT wheat cultivars have improved their nitrogen-use efficiency

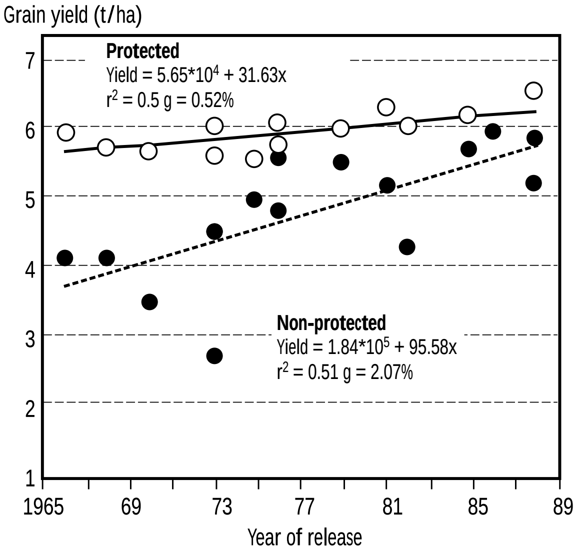

Figure 6.1. Grain yields for spring bread wheat varieties under fungicide-protected and non-protected conditions for normal plantings.
Source: Sayre et al. (1998).

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[29] Some of these varieties may have had ancestors that originated in more favorable environments.

(Ortiz-Monasterio et al. 1997). Waggoner (1994) has taken the data reported by Ortiz-Monasterio et al. and demonstrated an inward shift in unit yield isoquants defined over nitrogen and land (Figure 6.2). Over time, CIMMYT wheat lines have also shown increased tolerance to heat (Reynolds et al. 1998) and better tolerance to drought (Trethowan et al. 2001).

Wheat Yields in Farmers' Fields by Environment in Developing Countries

How have experimental yield gains translated into industry yield gains? As noted previously, this question is difficult to answer in ways that are useful for guiding wheat breeding programs or for evaluating the impacts of past research. Difficulties often result from the fact that experimental wheat yield data are classified by wheat growing environment, while industry yield data are classified by political units such as countries. Industry yield data can often be used to estimate returns to research for programs focused on particular political units, but they may not be suitable for addressing subtle questions about returns to research in different environments, or optimal future allocation of breeding effort across these environments.

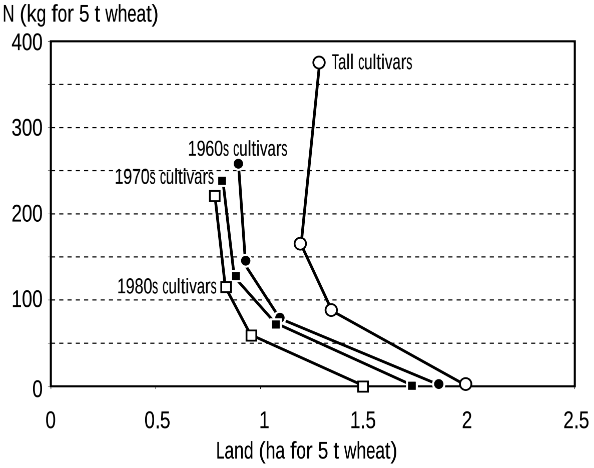

Figure 6.2. Land and nitrogen required to grow 5 tons of wheat.

Source: Waggoner (1994) and Ortiz-Monasterio et al. (1997).

In an effort to bridge the gap, we attempted to summarize developing country wheat yields in 1997 according to environment. For this exercise, the FAO country wheat production data were taken for five-year periods, centered on 1997, and averaged. This information was combined with data from the CIMMYT wheat ME database on yields in different production zones in each country.[30] The yields for different production zones for each country were then adjusted to make them consistent in relative terms with information from the ME database, and in absolute terms with country-level yields as reported by FAO. Area-weighted yields were subsequently aggregated across regions and environments.[31] Results for durum wheat were kept separate from those for bread wheat.

Tables 6.4 through 6.7 indicate the results of this exercise. As expected, ME 1 (irrigated spring bread wheat) is not only the most extensive environment in the developing world (Table 2.2), but it is also the highest yielding. Dry environments (ME 4) have the lowest yields. Overall spring bread wheat yields are highest in Asia and lowest in WANA and sub-Saharan Africa (Tables 6.4 and 6.5). Spring durum wheat yields tend to be lower in the aggregate than spring bread wheat yields, but they are slightly higher than spring bread wheat yields in ME 4A, where durum wheat is most widely grown (Table 6.6).

Yields of winter bread wheat in the developing world are higher than yields of spring bread wheat. This is entirely due, however, to high yields

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[30] Updated information for sub-Saharan Africa was obtained from Payne, Tanner, and Abdalla (1996).

[31] Because of the difficulty in separating irrigated from high rainfall winter wheat in the data, these environments (ME 7 and ME 8 for facultative wheat, and ME 10 and ME 11 for winter wheat) were not distinguished in our calculations.

Table 6.4. Yields of spring bread wheat by mega-environment, 1997, including China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All Spring bread wheat MEs
Sub-Saharan Africa	4.71	1.53	1.68	1.93			1.74		2.02
West Asia and North Africa	3.01	2.50		0.87					1.98
Asia	2.97	2.08				1.16	2.17	2.66	2.63
Latin America	4.90	3.04	1.71		1.56		1.56		2.31
All regions	**3.01**	**2.54**	**1.71**	**1.00**	**1.56**	**1.16**	**2.10**	**2.66**	**2.46**

Table 6.5. Yields of spring bread wheat by mega-environment, 1997, excluding China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All Spring bread wheat MEs
Sub-Saharan Africa	4.71	1.53	1.68	1.93			1.74		2.02
West Asia and North Africa	3.01	2.50		0.87					1.98
Asia	2.74					1.14	2.15		2.43
Latin America	4.90	3.04	1.71		1.56		1.56		2.31
All regions	**2.82**	**2.64**	**1.71**	**1.00**	**1.56**	**1.14**	**2.08**		**2.30**

Table 6.6. Yields of spring durum wheat by mega-environment, 1997 (including or excluding China).

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All Spring durum wheat MEs
Sub-Saharan Africa		0.97							0.97
West Asia and North Africa	3.12	2.36		1.19					1.56
Asia	2.17					0.97			1.00
Latin America	4.68	0.95			2.06				4.17
All regions	**4.15**	**1.99**		**1.19**	**2.06**	**0.97**			**1.69**

for this wheat type in China[32]. In WANA, another region in which winter wheats are widely grown, yields of winter bread wheat are lower than yields for spring bread wheat and slightly higher than yields for spring durum wheat (Tables 6.7 and 6.8). Only a small amount of winter durum wheat is grown in Turkey, and there yields are generally comparable to yields of winter bread wheat (Table 6.9).

Figures for spring habit wheat yields can be combined with adoption figures reported in Appendix B and Table 32 (taken from Byerlee and Moya 1993) to derive a rough estimate of yield gains by environment between 1990 and 1997. These comparisons can be made for four environments: irrigated (ME 1), high rainfall (ME 2), acid soils (ME 3), and drought (MEs 4A, 4B, and 4C). Calculations based on these assumptions suggest that in the 1990s, yield growth was high in drought environments not only because of Stage I effects caused by further adoption of MV wheat, but also because of Stage II yield growth for MV wheat planted in these environments (Tables 6.10 and 6.11). In contrast, ME 1 (irrigated) yield growth in the 1990s was almost entirely driven by MV (Stage II) yield growth, as adoption of MVs in

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[32] These wheats have long crop cycles, sometimes up to ten months. In contrast, spring wheats mature in four to six months, allowing a second and sometimes a third non-wheat crop in a year.

Table 6.7. Yields of winter bread wheat by mega-environment, 1997, including China.

Region	ME 7 / 8 Irrigated / high rainfall / facultative	ME 9 Drought / facultative	ME 10 / 11 Irrigated / high rainfall / winter	ME 12 Drought / winter	All facultative / winter bread wheat MEs
Sub-Saharan Africa		1.38			1.38
West Asia and North Africa	6.21	1.14	2.09	1.51	1.79
Asia	4.71	2.66	4.97	2.57	4.23
Latin America	3.26	2.40	4.00	2.40	3.33
All regions	**4.70**	**2.02**	**3.18**	**1.93**	**3.35**

Table 6.8. Yields of winter bread wheat by mega-environment, 1997, excluding China.

Region	ME 7 / 8 Irrigated / high rainfall / facultative	ME 9 Drought / facultative	ME 10 / 11 Irrigated / high rainfall / winter	ME 12 Drought / winter	All facultative / winter bread wheat MEs
Sub-Saharan Africa		1.38			1.38
West Asia and North Africa	6.21	1.14	2.09	1.51	1.79
Asia					
Latin America	3.26	2.40	4.00	2.40	3.33
All regions	**4.45**	**1.25**	**2.12**	**1.52**	**1.80**

Table 6.9. Yields of winter durum wheat by mega-environment, 1997 (including or excluding China).

Region	ME 7 / 8 Irrigated / high rainfall / facultative	ME 9 Drought / facultative	ME 10 / 11 Irrigated / high rainfall / winter	ME 12 Drought / winter	All facultative / winter durum wheat MEs
Sub-Saharan Africa					
West Asia and North Africa			4.80	1.45	1.85
Asia					
Latin America					
All regions			4.80	1.45	1.85

Table 6.10. Implied rate of yield gain for spring habit wheat MVs by mega-environment, 1990-1997, excluding China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought (residual moisture)
Sub-Saharan Africa		High				
West Asia and North Africa	Low	≤ 0		High		
Asia	Intermediate					High
Latin America	≤ 0	Intermediate	High		High	

Note: Low: 0.1-0.5 % annually; intermediate: 0.6-1.5 % annually; high: > 1.5% annually.

Table 6.11. Implied rate of yield gain for all spring habit wheat by mega-environment, 1990-1997, excluding China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought (residual moisture)
Sub-Saharan Africa		Low				
WANA	Low	High		High		
Asia	Intermediate					High
Latin America	≤ 0	Intermediate	High		High	

Note: Low: 0.1-0.5 % annually; intermediate: 0.6-1.5 % annually; high: > 1.5% annually.

ME 1 was essentially complete by 1990. Under these assumptions, MV yields in farmers' fields in ME 1 in South Asia grew at a little over 1% per year in the 1990s. This is consistent with the yield growth rate often assumed for irrigated wheat in farmers' fields on the basis of experimental yield gains (Byerlee and Moya 1993). Irrigated spring wheat yields appeared to have grown more slowly in WANA, however, and they actually decreased in Latin America.[33] Rates of yield growth in ME 2 (high rainfall) appear to have varied widely.

Varying rates of yield growth by environment and region partially result from inaccurate estimates of area, production, and yield by environment. As we have noted, it is difficult to estimate these parameters for wheat-growing environments when available data refer to political units, rather than MEs. In an alternative approach, we estimated yield growth for five environments based solely on country data. For ME 1 (irrigated), ME 2 (high rainfall), ME 4A (Mediterranean-type drought), and ME 5 (hot), we aggregated data from countries that have 50% or more of their wheat area in these environments. Most other MEs do not constitute a sufficiently large proportion of any individual country to make this a reasonable procedure. However, the fact that most acid soil wheat area is in Brazil and most Brazilian wheat area is acid soil allowed us to estimate yield growth for ME 3 based on Brazilian data.

Using this approach, we can see that in the early 1960s, yields were slightly higher in countries dominated by irrigated environments and slightly lower in countries dominated by acid soils and/or dry, hot environments. In the early Green Revolution years (mid-1960s to mid-1970s), wheat yields in both irrigated and hot environments grew very rapidly as semidwarf varieties diffused widely. In the immediate post-Green Revolution period (mid-1970s to mid-1980s), wheat yields grew very rapidly in all environments. Further diffusion of semidwarf wheats, newer varieties, and more efficient input management probably all contributed to yield growth in areas where semidwarfs had already spread. Initial diffusion of semidwarf wheats (Stage I yield gains) probably played a substantial role in boosting industry yields in dry areas (CIMMYT 1989). Since the mid-1980s, wheat yield gains appear to have slowed in all environments, but they have continued to increase at a substantial rate in countries with large areas of irrigated wheat. Yield growth has been less consistent in other environments and may even have turned negative in countries in which a great deal of wheat is grown under early drought conditions (Table 6.12). However, in some of these countries, it is possible that the results of our earlier analysis—that yield growth continued in less favored areas and decelerated in more favored areas—still hold.

Research spillovers from irrigated environments thus seem to have contributed to wheat yield gains in less favorable environments. Over longer periods of time, it appears to have been easier to sustain rapid yield growth in irrigated environments than other environments. The slower rates of yield gain in high rainfall environments compared to irrigated wheat environments may have resulted from more complex disease pressure in high rainfall areas.

Summary

Experimental data strongly support the contention that wheat breeders have continued to improve wheat yields in the post-Green Revolution period. Even abstracting from the semidwarfing characteristic, it appears likely that improvements in disease and lodging resistance and increases in yield potential have been the most important

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[33] In an example from Mexico's Yaqui Valley, Sayre (1996) and Bell et al. (1995) show a slowdown in yield growth rate in farmers' fields over a similar period in which Sayre, Rajaram, and Fischer (1997), and Reynolds, Rajaram, and Sayre (1999) indicate no deceleration in experimental wheat yield growth.

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 and better-watered environments than in drier areas. However, during certain periods, intelligently designed, spillover-based research has brought rapid experimental yield gains to less favorable environments, starting in most cases from a much lower base yield.

Although the evidence is not conclusive, aggregate industry-level wheat yield data categorized by environment and region suggest that over a long period of time, yield gains have been most consistent in irrigated wheat environments. In recent years, these yield gains may have slowed[34] in these environments, while spillovers have brought both Stage I and Stage II benefits to less favorable environments. This result, particularly the decelerating yield growth in irrigated areas, is similar to the less aggregated analysis of Bell et al. (1995), Sayre (1996), and Byerlee (1992). Yield levels in less favorable environments nevertheless remain considerably lower than those in irrigated or higher rainfall areas.

Several caveats need to be applied to the analysis. First, it would be useful to have better individual country production and yield data by major environment. Geographic information system (GIS) efforts (which are already in process) combined with thorough investigation of available country-level data will play an important role in improving the reliability of environment-specific analysis.[35]

Second, calculations of additional yield and production in different environments will need to become more sophisticated. Direct translation of experimental yield gains into industry yield gains no longer tracks yields very well in a variety of wheat growing environments. Researchers who wish to estimate the benefits of wheat improvement research will increasingly need to formulate careful scenarios of what has happened where research has taken place and what would have happened had that research not taken place. The recent revival of interest in evaluating the benefits of maintenance research is welcome.

Third, it would also be good to begin analyzing non-yield benefits due to improvements in industrial quality.

Table 6.12. Wheat yield gains in developing countries, 1966-2000.

	Environment				
	Irrigated[a] (ME 1)	High rainfall[b] (ME 2)	Acid soils[c]	Dry[d] (ME 4A)	Hot[e] (ME 5)
Yield, 1961-65 (t/ha)	0.94	0.84	0.71	0.73	0.74
Yield gains, 1966-77 (%/yr)	3.90	1.92	-1.20	1.06	3.62
Yield gains, 1977-85 (%/yr)	3.59	3.48	7.87	4.62	6.31
Yield gains, 1985-2000 (%/yr)	2.16	0.95	0.99	-0.73	0.80
Yield gains, 1990-97 (%/yr)	2.04	0.07	4.74	0.51	2.34

Source: Calculated from FAO production statistics. Environments defined using CIMMYT mega-environment database.

[a] Eight countries with 50% or more wheat area planted to irrigated spring habit wheat. India and Pakistan account for 94% of total area. Does not include countries such as Bangladesh or Sudan where higher growing season temperatures prevail.

[b] Seven countries with 50% or more wheat area planted to high rainfall spring habit wheat. Ethiopia accounts for 75% of total area.

[c] Brazil only.

[d] Nine countries with 50% or more wheat area planted to low rainfall, pre-flowering moisture stress spring habit wheat. Morocco, Syria, Algeria, Iraq, and Tunisia account for 96% of total area. Does not include two other sub-categories of drought environment.

[e] Four countries with 50% or more wheat area planted to hot environment spring habit wheat. Includes Bangladesh, Myanmar, Sudan, and Paraguay. In recent years Bangladesh wheat area has risen from about 50% to about 70% of total.

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[34] In recent years, end-use quality of wheat varieties has increased, which may have also contributed to lesser yield increases than otherwise possible.

[35] In the interim, updates to the CIMMYT ME database, which is now more than 15 years old, such as the one performed for sub-Saharan Africa by Payne, Tanner, and Abdalla (1996), have proven quite helpful.