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CIMMYT

WORLD WHEAT OVERVIEW AND OUTLOOK 2000-2001

Developing No-Till Packages for Small-Scale Farmers

Javier Ekboir, Editor

Part 2 Are Marginal Wheat Environments Catching Up?

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Introduction

About one-third of the developing world's wheat area is located in environments that are regarded as marginal for wheat production because of drought, heat, and soil problems (CIMMYT 1997). Nearly one-third of the area planted to bread wheat and about three-fourths of the area planted to durum wheat suffer from severe drought stress during the growing season (Byerlee and Morris 1993).

Despite these limitations, the world's dry and difficult cropping environments are increasingly crucial to food security in the developing world. Worldwide, investment in irrigation infrastructure continues to fall, while population growth and demand for wheat are rising. Gains in wheat productivity in marginal environments are important because it is unlikely that increased productivity in the favorable environments will be sufficient to meet the projected growth in demand for wheat from the present to 2020. The demand for wheat is projected to be 40% greater than its current level of 552 million tons by 2020 (Rosegrant et al. 1997). Improved productivity in marginal areas would improve food security among the poorer populations that live there.

It is widely believed that the Green Revolution had very little effect in marginal environments, where the harsh agricultural conditions and slow spread of Green Revolution technology resulted in very modest yield gains. For some time, the development community has been concerned about progress in marginal areas and the level of research resources allocated to those areas (see Byerlee and Morris 1993).[1] This section of our report provides new information to address these issues by answering the question: Is growth in wheat yield potential in marginal environments approaching the levels attained in favorable environments? More specifically, we:

- describe breeding research that improved productivity in marginal environments (with an emphasis on CIMMYT's wheat breeding strategies);
- estimate rates of growth in wheat yield potential in marginal and favorable environments;
- examine the crossover and spillover of wheat varieties from favorable to marginal environments;
- identify implications for wheat productivity growth in marginal environments; and
- discuss future challenges for marginal environments.

Data for this study were obtained from CIMMYT's Elite Selection Wheat Yield Trial (ESWYT), grown in 246 locations in 65 countries between 1979 and 1999, and from CIMMYT's International Spring Wheat Yield Nursery (ISWYN), grown in 411 locations in 82 countries between 1964 and 1995.[2] Nurseries such as the ISWYN and ESWYT are one way in which breeders in developing countries regularly gain access to (and exchange) a large number of new wheats bred by CIMMYT and partners in national research programs. This system of breeding and exchanging germplasm and information is often referred to as "the international wheat research system," and its role in wheat yield trends in marginal environments will be discussed later.

[1] Note that Byerlee and Morris (1993) found that the level of investment in marginal environments was adequate, based on the proportional value of wheat production in those environments and making appropriate adjustments for relative poverty levels, the strength of local breeding efforts, and the expected rate of research progress.

[2] ESWYT tests the adaptation of high-yielding, disease-resistant, advanced wheat lines bred by CIMMYT. The most promising lines from ESWYT are included in the ISWYN trials, which are grown in many more locations. ISWYN trials are designed to test the adaptation of advanced spring wheat lines as well as varieties from major wheat areas around the world under different environmental conditions (CIMMYT 1979).

Data on spring wheat varieties planted in 1990 and 1997, including their pedigrees, year of release, area planted to each variety, and target mega-environment, were obtained from the CIMMYT Wheat Impacts database. A mega-environment (ME) is a broad, frequently transcontinental but not necessarily contiguous area with similar biotic and abiotic stresses, cropping system requirements, consumer preferences, and possibly volume of production (Rajaram, van Ginkel, and Fischer 1995; Pingali and Rajaram 1999). Mega-environments usually encompass more than one country and are useful for defining breeding objectives, because each ME comprises millions of hectares that are relatively homogeneous for wheat production (Dubin and Rajaram 1996).

The ISWYN data were grouped into two periods: the Green Revolution period (1964-78) and the post-Green Revolution period (1979-95). The ESWYT data (1979–99) were taken from the latter period. The average of the top three wheat yields for each location per year was used in the analysis. Locations were grouped by ME.[3]

Wheat Breeding Strategies for Marginal Environments

Have wheat breeding strategies had an impact on productivity growth in marginal areas? Since 1977, CIMMYT's wheat breeding efforts have focused on serving all agro-ecological regions of the developing world (Rajaram 1995). In breeding wheat for marginal environments, CIMMYT researchers combine wheat varieties with high yield potential with varieties that are adapted to particular abiotic stresses prevalent in marginal areas, especially drought, heat, and acid soils.

In the quest for wheat germplasm that is tolerant to drought, for example, researchers have developed varieties that possess the high yields and input responsiveness of varieties developed for favorable environments as well as the drought tolerance and water-use efficiency of germplasm for semiarid areas. CIMMYT's Veery lines and the advanced line Nesser are two examples of this breeding method. Although the Veery lines were developed originally for favorable areas in the early 1980s, they have adapted well in less favorable environments, except those with rainfall below 300 mm/yr. The Veery wheats can be described as genetic systems that manifest high yield performance in favorable environments and drought adaptation in unfavorable environments (Pingali and Rajaram 1999), and they have been widely used as parent material in breeding programs. One of the latest Veery progeny is Baviacora M92, which unites adaptation to optimum as well as stressed growing conditions. Nesser, mentioned earlier, performs extremely well under drought. This advanced line was bred in favorable environments in Mexico and carries a combination of input efficiency and high yield responsiveness. Its performance is similar to that of the Veery lines.

For selecting cultivars that tolerate heat stress, yield remains the most reliable criterion (for example, in yield trials), because high temperatures affect yield components and indirectly lower yields. The yield criterion cannot be used when selecting for heat tolerance in segregating populations, however, because grain from a large, unmanageable number of lines needs to be harvested, threshed, and weighed. The CIMMYT Wheat Program uses a combination of empirical observation and quantitative measurements to select bread wheat that tolerates heat stress. Although an experienced breeder can make subjective but fundamentally correct judgments on biomass, number of spikes, tillering capacity, stand establishment, leaf senescence, and grain-filling period, this empirical judgment must be supported by careful yield trial analysis and quantitative measurements to substantiate the associations of characters involved in heat tolerance (Morgunov 1995). Varieties tolerant to heat stress have been selected in Upper Egypt and Sudan, including El Nielain, Giza 160, Giza 164, and Debeira. The Indian varieties Kanchan and Sonalika have not only been accepted widely in eastern India for their heat tolerance, but have also been released in Bangladesh, where heat stress is a problem.

Apart from drought and heat stress, marginal environments can suffer from problems of acid soils, which have levels of aluminum that can be toxic to wheat plants. CIMMYT began to collaborate with Brazilian scientists in the mid-1970s to combine Brazilian wheats' tolerance to aluminum toxicity with Mexican wheats' semidwarf

[3] The authors thank Hans-Joachim Braun, Man Mohan Kohli, Mohamed Mergoum, Wolfgang Pfeiffer, Richard Trethowan, and Maarten van Ginkel of the CIMMYT Wheat Program for assistance in classifying ESWYT and ISWYN locations by ME.

stature, high yield potential, and wide adaptation. The Brazilian wheats contributed valuable characteristics aside from aluminum tolerance, such as longer leaf duration, increased phosphorus uptake efficiency, and resistance or tolerance to leaf spotting diseases. The CIMMYT wheats contributed improved rust and mildew resistance, a better agronomic type (better plant type, shorter and stronger straw, and larger and more fertile spikes), and better heat and drought tolerance.

After about a decade, semidwarf wheats with aluminum tolerance were available. From 1976 to 1989 in the acid soil environments of Rio Grande do Sul, Brazil, wheat yields rose by 3.1% per year (Byerlee and Moya 1993). This high yield gain may have resulted from the CIMMYT-Brazil cooperative breeding program. The distribution of wheats produced through that program has benefited other countries with acid soil problems as well, including Madagascar, Zambia, Kenya, Tanzania, Rwanda, Cameroon, and Ecuador (Pingali and Rajaram 1999).

These brief examples of stress tolerance in marginal environments appear to indicate that the principle of maximizing spillover benefits—in breeding terms, the use of exceptional wheats bred in favorable environments to develop wheats that have improved productivity in less favorable environments—has worked well. These benefits are described in greater detail later.

Growth in Wheat Yield Potential

How do trends in wheat yield potential compare in favorable and marginal environments? As noted, the locations included in the ESWYT and ISWYN trials were classified by ME. ME1 (irrigated) and ME2 (high rainfall) are considered to be highly favorable wheat production environments, whereas ME4 (drought prone) and ME5 (high temperature) are considered to be marginal.[4] Wheat yield growth rates (%/yr) were estimated for each of these four MEs in the ESWYT and ISWYN using the log-linear regression model described in Part 4.

Analysis of the ESWYT data indicates that growth in wheat yield potential in ME4 and ME5 has occurred at a substantially faster rate than in ME1 and ME2. Wheat yields in ME4 grew by about 3.5%/yr (approximately 88 kg/yr), the highest of the four MEs (Figure 1). This rate of yield gain was similar to the rate reported earlier for acid soil environments (3.1%/yr). In ME5, wheat yield potential grew by a rate of 2.1%/yr (46 kg/yr). On the other hand, ME1 and ME2 sustained growth rates in wheat yield potential of about 1%/yr (53.5 kg/yr and 62.5 kg/yr, respectively).

The same trend was found when the ESWYT data were verified using ISWYN data (1964-95). In the post-Green Revolution period (1979-95), wheat yield potential in marginal environments grew at double or more than double the rate of growth in favorable environments. Growth rates in wheat yield potential in ME4 and ME5 were 2.75% (70.5 kg/yr) and 2.5% (72.3 kg/yr), respectively (Figure 2).

An analysis of average wheat yield potential in favorable and marginal environments using ESWYT and ISWYN data also revealed a rising trend (Figures 3 and 4). The increase in average yield potential and the rapid wheat yield growth rates seen in marginal environments indicate the enormous potential for improving wheat productivity in those areas.

These findings are consistent with results of a recent analysis (Trethowan 2001), based on data from the Semi-Arid Wheat Yield Trial (SAWYT), of

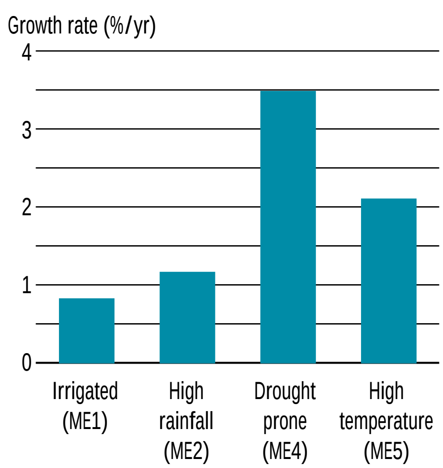

Figure 1. Trends in wheat yield growth rate by mega-environment (ME), ESWYT, 1979-99.

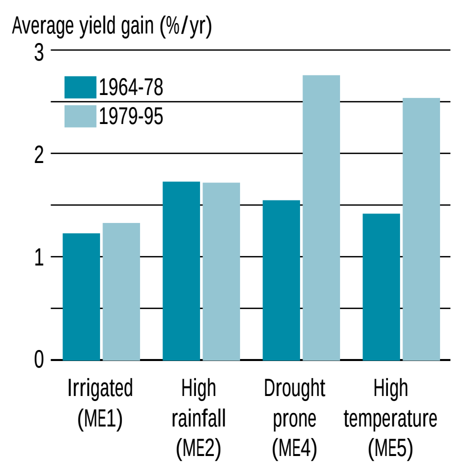

Figure 2. Rate of yield gain in favorable and marginal wheat environments, ISWYN, 1964-95.

4 CIMMYT recognizes a number of major MEs, some of which are divided into sub-MEs.

progress in improving wheat yields in low- and intermediate-yielding environments (Figure 5). Low-yielding environments were defined as environments with wheat yields of less than 2.5 ha, and intermediate-yielding environments had wheat yields of 2.5-4.5 ha. In low-yielding environments, the rate of progress in improving wheat yields (expressed as the yield advantage of the best five lines over the local check variety) rose from 12% in 1991 to 38% in 1997. Likewise, in intermediate-yielding environments, the rate of yield progress rose from 16% to 45% over the same period. These results imply that, regardless of which data (ESWYT, ISWYN, or SAWYT) are used in the analysis, wheat yield potential increased markedly in marginal environments.

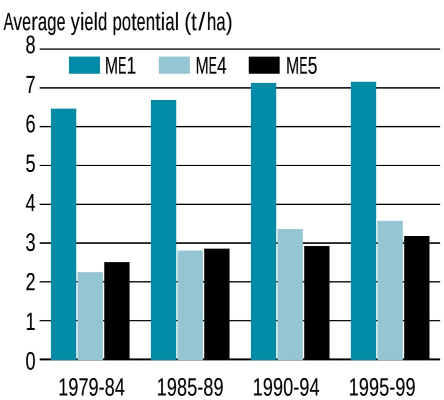

Figure 3. Average wheat yield potential by mega-environment (ME) and period, ESWYT, 1979-99.

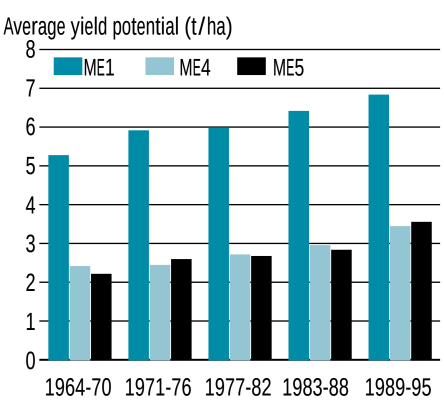

Figure 4. Average wheat yield potential by mega-environment (ME) and period, ISWYN, 1964-95.

Rates of Adoption of Modern Varieties

Between 1967 and 1989, most of the growth in area planted to modern varieties (MVs) of wheat (over 16 million hectares) occurred initially in wetter rainfed areas, moving only gradually to drier rainfed areas (Byerlee 1994). In more recent years, rates of adoption of MVs in marginal areas are catching up with those seen in favorable areas (Figures 6 and 7). Adoption of MVs was higher in 1997 (Figure 7) than in 1990 (Figure 6) in most regions, with the exception of sub-Saharan Africa, where ME5 was represented only by four MVs grown in Sudan. The rate of MV adoption was slightly lower in West Asia and North Africa (WANA) than in other regions because large areas in WANA are still devoted to landraces.[5] The increase in wheat production resulting from more rapid adoption of MVs in marginal areas is discussed later in this section.

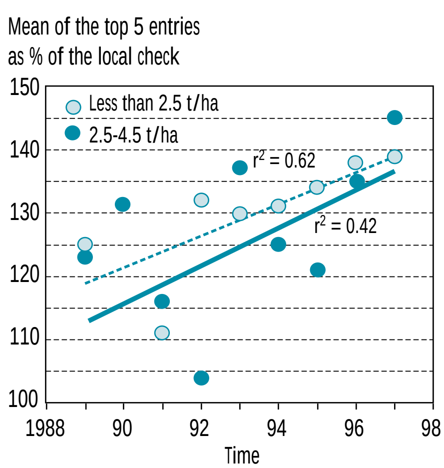

Figure 5. Trends in yield over time in low and intermediate yielding environments.
Source: Trethowan (2001).

Crossover and Spillover of Varieties from Favorable to Marginal Environments

Both crossovers and spillovers have influenced yield trends in marginal environments. In this report, a crossover is defined as occurring when the same wheat variety is planted in both favorable and marginal

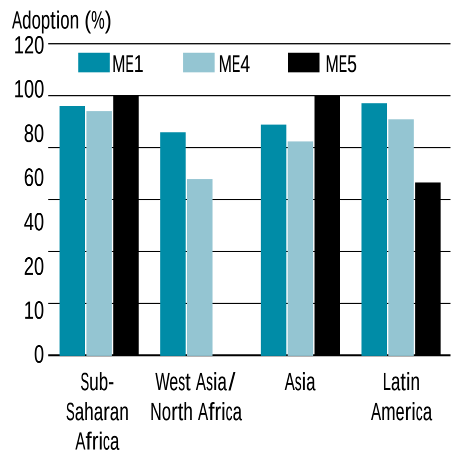

Figure 6. Percentage adoption of modern wheat varieties by mega-environment and region, 1990.

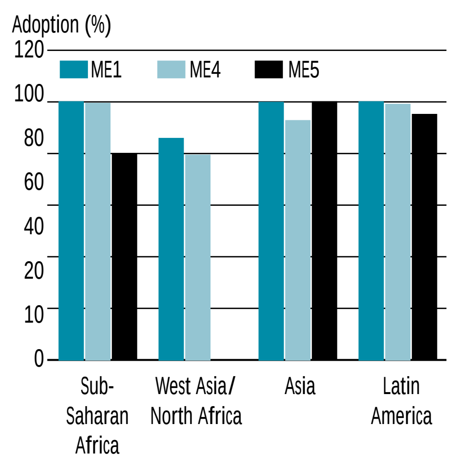

Figure 7. Percentage adoption of modern wheat varieties by mega-environment and region, 1997.

5 Landraces constituted slightly less than 20% of the area planted to spring durum wheats in WANA (Heisey, Lantican, and Dubin 1999).

environments in the same period. A spillover occurs when a wheat variety developed for ME1 or ME2 is used to breed a variety that is later grown in ME4 or ME5. Spillovers can be direct or indirect. A direct spillover occurs when both parents of the ME4 or ME5 variety are from ME1 or ME2 varieties. An indirect spillover occurs when one parent of the ME4 or M5 variety is a variety from ME1 or ME2.

In 1997, crossover varieties from ME1 and ME2 (released between 1973 and 1986) occupied 19.5% (about 3 million hectares) of the area planted to MVs in ME4 and ME5 (Table 1). The two crossover varieties that occupied the most area (about 1.1 million hectares each) were HD-2285 and Sonalika. (Sonalika, originally bred in Mexico by CIMMYT and first released in India, matures very early and thus escapes heat exposure.) Although most durum varieties are grown in marginal areas, three crossover durum varieties were identified: Mexicali, Cocorit, and Waha. Pfeiffer et al. (2001) claimed that the adoption of such cultivars as Mexicali-75 and Cocorit-71 shows the international reach of CIMMYT's durum breeding program.

The direct spillover of wheat varieties from ME1 or ME2 to ME4 or ME5 decreased slightly from 1990 to 1997 (Figure 8), whereas indirect spillovers were about the same in 1990 and 1997. The percentage of area planted to varieties targeted specifically for ME4 and ME5 (i.e., varieties that were not bred from ME1 or ME2 varieties) increased slightly in 1997.

The international wheat research system, described earlier, plays a key role in maximizing the spillover benefits of research for marginal environments. As noted previously, a primary strategy of CIMMYT's wheat breeding program is to combine the yield responsiveness of varieties developed in ME1 and ME2 with the adaptation to drought and other stresses characteristic of varieties in marginal environments such as ME4 and ME5. The resulting varieties are made available through the international wheat research system. Investments in this breeding strategy are likely to be cost-effective in marginal areas, because the spillover benefits from favorable environments are likely to be high. Using an estimated "spillover matrix" based on ISWYN data, Maredia (1993) and Maredia and Byerlee (1999) showed that large global research spillovers for wheat have contributed to the increase in growth in wheat yield potential in marginal environments. Wheat production in WANA, for example, has benefited greatly from spillovers.

How Has Breeding Research Affected Wheat Production?

There are two sources of production increases from wheat breeding research: the expansion of area planted to MVs and the replacement of older MVs with newer ones. Data from the CIMMYT Wheat Impacts database and the rates of wheat yield gain generated from the ESWYT and ISWYN analyses were used to estimate production increases from these sources in the period from 1990 to 1997.[6]

As a result of expanding MV area and the replacement of older MVs, an additional 38 million tons of wheat was produced. Of this production increase, 10.7 million tons came from marginal environments.

Table 1. Wheat varieties planted both in ME1 or ME2 and in ME4 or ME5, 1997.

	Area (000 ha)	
Variety	**ME1 & ME2**	**ME4 & ME5**
Pavon F76 (1976)	208.8	27.8
Mexicali (1978)	13.5	52.3
Cocorit (1975)	13.3	54.8
Veery (1985)	1798.6	130.5
Debeira (1982)	3.9	169.0
Waha (1986)	5.8	345.7
Sonalika (1973)	5.5	1127.5
HD-2285 (1985)	8.1	1137.0
Total area	**2057.5**	**3044.5**

Crossover = 19.5% of the total ME4 and ME5 MV planted area.

Note: Figures in parenthesis are dates of release.

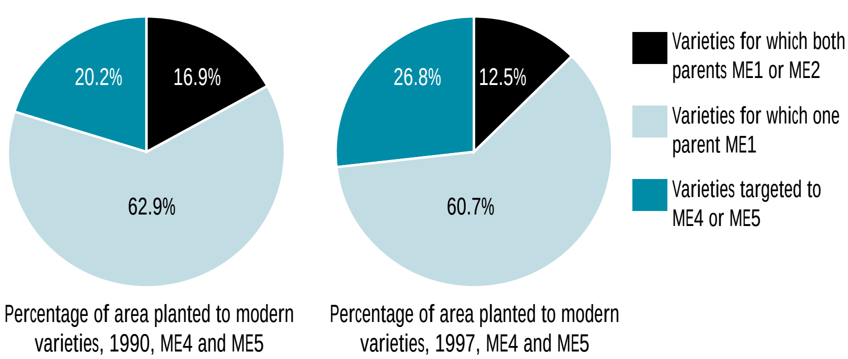

Figure 8. Spillovers of modern wheat varieties from favorable environments (ME1, ME2) to marginal environments (ME4, ME5).

[6] Data from China and South Africa were excluded from the analysis to avoid biased estimates of production increases resulting from an expansion in MV area. The wheat areas of both countries were covered fully only in the most recent (1997) wheat impact survey.

The additional wheat production resulting from expanding MV area over 1990–97 was about 22.8 million tons. How much of this additional wheat production came from each of the four MEs? ME4 produced the highest amount (9.9 million tons) (Figure 9), followed by ME1 (an increase of 9.2 million tons) and ME2 (4.7 million tons). There was a production loss in ME5, however, because MV area diminished in Sudan in 1997. The declining international price of wheat may also have influenced Sudan and other (mostly ME1) countries such as Brazil, Mexico, Zimbabwe, and Nigeria to reduce their wheat area in 1997.

The additional wheat production resulting from the replacement of older MVs with new ones over 1990-97 was 15.2 million tons; of this, 13.3 million tons came from favorable MEs. The marginal MEs contributed 1.85 million tons (1.3 million tons from drought-prone ME4) (Figure 10). These increases concur with Byerlee's (1994) finding that the release of newer generations of MVs in areas already sown to MVs—particularly favorable environments such as ME 1 and ME2—has contributed significantly to productivity growth. Other studies that have examined the replacement of MVs have concluded that factors affecting the rate of replacement include the perceived yield advantage of the new varieties, the performance of a variety when planted late, the yield deterioration of the old variety, the transfer of knowledge about the new variety from farmer to farmer, the seed price, cultivated area, contact with information sources, membership in an organization, number of oxen owned, and farming experience (see Heisey 1990; Heisey and Brennan 1991; Alemu Hailye et al. 1998; and Regassa Ensermu et al. 1998).

Future Challenges

Despite the increasing growth in wheat yield potential in marginal environments, large challenges remain to be addressed to meet future wheat demand in these areas. These challenges include drought stress in environments where there is no rainfall during the growing period (where farmers sow wheat on stored moisture) or in environments with rainfall levels of below 300 mm/yr; the need to combine drought tolerance with heat tolerance; nutrient deficiencies (boron and zinc); soil-borne stresses; and salinity.

A concerted effort to develop germplasm that specifically targets these problems would significantly increase productivity in marginal environments. For instance, Trethowan (2001) has described plans to disseminate a set of genotypes that differentiate for key soil-borne stresses over the next few years. This trial should improve our understanding of limitations to the adaptation of wheat in many key marginal areas.

Although MVs will play a role in increasing yields in marginal environments, they may not be the only or even the primary stimulus for rapid technical change. The development of improved crop and resource management techniques will greatly benefit marginal environments. Since moisture is the major constraint in marginal areas, the main focus of technological innovation must be moisture conservation and improvements in water-use efficiency. Poor soils are also a problem in many marginal environments, and productive and sustainable agriculture in the developing world requires cropping systems and crop varieties that are adapted to marginal lands and can help reconstruct poor soils (Bosemark 1993). Finally, the diversification of crops and cropping systems is also important in improving and/or sustaining incomes in marginal environments, and research must take this requirement into consideration.

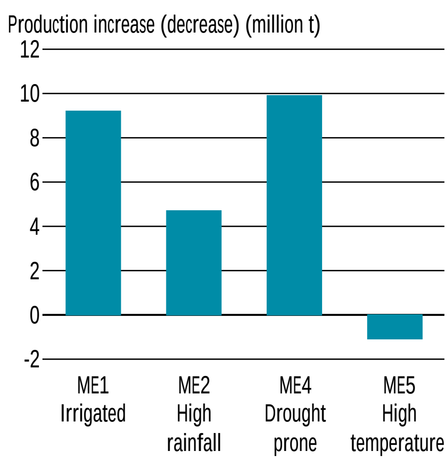

Figure 9. Production increase (decrease) resulting from addition (reduction) in area planted to modern wheat varieties by mega-environment (ME), 1990-97.

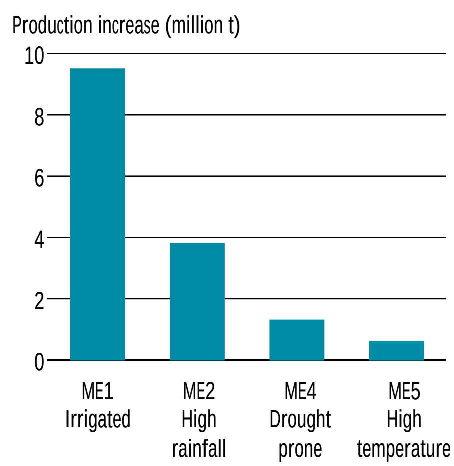

Figure 10. Production increase resulting from the replacement of older modern wheat varieties with newer ones by mega-environment (ME), 1990-97.