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Is research on marginal lands catching up? The case of unfavourable wheat growing environments☆

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Abstract

It is widely believed that the Green Revolution had very little effect in unfavourable or marginal environments. Many researchers have been concerned about the slow progress of technical change in marginal environments and the level of research resources allocated to these areas. This paper provides empirical evidence that there has been significant growth in wheat yield potential in marginal environments, especially during the post-Green Revolution. International yield trial data, covering all major wheat growing environments from 1964 to 1999, were used in estimating the growth in wheat yield potential and changes in yield variability. The global database on wheat varietal adoption and yield gains based on estimated wheat yield growth rates were used to determine production increases due to wheat breeding research. Results show greater progress in shifting the wheat yield frontier in marginal areas, particularly in drought and high temperature environments. Furthermore, yield variability in marginal environments has notably declined, while it has increased slightly in favourable environments. While initial gains came from crossover of varieties from favourable environments, targeted breeding efforts have contributed significantly to more recent productivity growth in marginal environments. Increased production from marginal environments accounted for around 25% of the total wheat production increase in 1997. These findings show greater progress in wheat research and the huge potential of improving wheat productivity in unfavourable environments.

Keywords: Mega-environment; Yield potential; Yield variability; Production increase; Crossover; Spill-over

1. Introduction

The world's dry and difficult cropping environments, the so-called unfavourable or marginal environments, are becoming increasingly crucial to food supplies and food security in the developing world. Future gains in food productivity (considering the partial factor productivity measure, yield) in marginal environments are important because it is unlikely that increased productivity in favourable environments will be sufficient to meet projected growth in demand for food from the present to 2020. The demand for food grains in developing countries is projected to increase by 49% (557 Mt) between 1997 and 2020 (Rosegrant et al., 2001). Improved productivity in marginal areas would also have a major impact on the livelihoods and food security of 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 the slow spread of Green Revolution technology resulted in very

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modest yield gains. For some time, the development community has been concerned about slow progress of technical change in these areas and the level of research resources allocated to them (Byerlee and Morris, 1993). The experience of wheat, however, has been contrary to the above trends for food grain crops in the developing world. This paper provides empirical evidence that there has been significant growth in wheat yield potential in marginal environments, especially during the post-Green Revolution, resulting in an increase in wheat supply from these environments.

Wheat breeders classify the developing world's spring wheat growing areas into six distinct mega-environments (MEs): irrigated (ME 1); high rainfall (ME 2); acid soil (ME 3); drought prone (ME 4); high temperature (ME 5); and high latitude (ME 6) environments. A ME is a broad, frequently transcontinental but not necessarily contiguous area occurring in more than one country, with similar biotic and abiotic stresses, cropping system requirements, volume of production and, possibly, consumer preferences (Pingali and Rajaram, 1999). The MEs are useful for defining breeding objectives because each ME covers millions of hectares that are relatively homogeneous for wheat production (Dubin and Rajaram, 1996).

ME 1 and ME 2 are commonly referred to as favourable wheat growing environments, while the rest are considered unfavourable or marginal wheat growing environments. Irrigated and high rainfall wheat growing environments account for approximately 60% of total wheat area in the developing world and close to 75% of total wheat production. Unfavourable wheat production environments jointly account for 40% of developing country wheat area and 25% of wheat production. Among the unfavourable environments, the drought prone environments (ME 4) are relatively more important, accounting for 25% of wheat area and 13% of wheat production. Acid soil (ME 3) and high temperature (ME 5) environments are locally important, the former in Brazil and Central Africa, and the latter in parts of Bangladesh, India, Paraguay and Mexico (van Ginkel et al., 2000).

The first gains in wheat productivity were seen in irrigated and high rainfall environments, or the so-called favourable production environments. By 1977, 83% of wheat area in the favourable environments was planted to modern, high yielding varieties (Byerlee and Moya, 1993). By 1997, this figure was close to 100% (based on the 1997 CIMMYT Wheat Impacts survey). The initial yield boost of 35–40% in farmers' fields was followed by a period of less dramatic but nonetheless steady yield growth, during which second and third generation varieties with higher yield potential and increased disease resistance replaced original improved varieties (Byerlee and Moya, 1993).

Rainfed environments, marginal for wheat production, also benefited from technological change. Up to until the early 1980s, productivity benefits in marginal environments came from varieties crossing over from favourable environments, i.e., varieties bred for favourable conditions grown under marginal conditions. However, by 1990, approximately 30% of all spring wheat varieties released were bred specifically for dryland environments.

The strategies for varietal improvement for marginal environments have evolved over time. In the immediate post-Green Revolution period, the emphasis was on maximising spill-over benefits from technical gains in favourable environments. In breeding terms, this means the use of exceptional wheat varieties bred in favourable environments to develop wheat varieties that have improved productivity in less favourable environments. The resulting varieties for marginal environments have one or both parents from ME 1 or ME 2 environments. Several examples of the successful use of ME 1 and ME 2 germplasm in breeding for marginal environments are cited in Pingali and Rajaram (1999). It was only since the 1990s that research emphasis shifted to developing breeding pools composed exclusively of marginal environment germplasm, releasing varieties that do not have ME 1 and ME 2 parents (although they could have ME 1 or ME 2 grandparents and great grandparents).

Using international yield trial data covering all major wheat growing environments worldwide from 1964 to 1999, and using the global database on wheat varietal adoption, this paper

1. estimates growth in wheat yield potential in both favourable and unfavourable or marginal environments during the Green Revolution and post-Green Revolution periods;
2. estimates changes in variability of wheat yields over time for both favourable and marginal environments;

3. examines crossover and spill-over of wheat varieties from favourable to marginal environments; and
4. assesses the impact of improved varieties on wheat productivity growth in marginal environments.

2. Data sources and methods

2.1. Data sources

Two sets of multi-country, multi-location long-term yield trial data were used in estimating growth in yield potential in favourable and marginal wheat growing environments. Marginal environments considered in this study are the drought prone (ME 4) and high temperature (ME 5) environments. As summarised in Table 1, the first set of yield data used in the study were obtained from the International Spring Wheat Yield Nursery (ISWYN) in 411 locations in 82 countries between 1964 and 1995, and the second set from the Elite Selection Wheat Yield Trial (ESWYT) in 276 locations in 65 countries between 1979 and 1999. The distribution by ME of ISWYN and ESWYT locations are summarised in Table 1 (see Payne et al., 2002 for details on data sets and methodologies used in yield trials). The ISWYN data set enables us to examine trends in yield potential and changes in variability of wheat yields in the Green Revolution and post-Green Revolution periods, while the ESWYT data set allows us to provide additional validation of post-Green Revolution results.

Both ISWYN and ESWYT are coordinated and managed by the International Maize and Wheat Improvement Center (CIMMYT) to

- provide researchers with an opportunity to assess the performance of their advanced lines over a wide range of climatic, soil and disease conditions;
- serve as a source of information on adaptation;
- allow local research and extension workers to compare the performance of new varieties from other countries; and
- provide a source of new and valuable genetic variability which cooperating countries may use directly or in crosses within their breeding programs.

ISWYN experiments were designed to study the performance of some of the most important varieties and materials from major wheat growing areas of the world, under different environmental conditions. In contrast, ESWYT was designed to test the adaptation of high yielding, disease resistant, advanced (or elite) lines bred by CIMMYT in limited locations around the world. Some varieties from other countries tested in ISWYN also had some CIMMYT ancestry, so CIMMYT decided to concentrate on testing its own materials targeted for specific environments and discontinued ISWYN after 1995.

Data on spring wheat varieties planted in 1990 and 1997, including pedigrees, year of release, area planted to each variety, and targeted ME were obtained from the CIMMYT Wheat Impacts database which includes all data from the 1990 and 1997 wheat

Table 1
Summary of data sources

Data source (number of locations)	ME 1[a] (irrigated)	ME 2 (high rainfall)	ME 4 (drought prone)	ME 5 (high temperature)
Experimental data				
ISWYN[b]				
30 yield nurseries (1964–1995) in 411 locations	196	101	72	42
ESWYT[c]				
19 yield trials (1979–1999) in 276 locations	142	64	38	32
Farm-level adoption data				
CIMMYT Wheat Impacts database				
1990 wheat impacts survey in 38 countries, 1966–1990				
1997 wheat impacts survey in 36 countries, 1966–1997				

[a] Mega-environment.
[b] International Spring Wheat Yield Nursery.
[c] Elite Selection Wheat Yield Trial.

impacts surveys. Pedigree management information developed by the CIMMYT Wheat Program was also used for thorough pedigree analysis of each wheat variety planted in 1997. Heisey et al. (2002) provide detailed information on how these data were collected. In both the 1990 and 1997 wheat impacts surveys, questionnaires were sent to the national agricultural research systems (NARS) in developing countries. In the 1990 study, 38 countries, accounting for nearly 70% of the wheat area in the developing world, completed the survey. In 1997, 36 out of the 41 countries, representing more than 80% of the wheat area in the developing world, responded to the survey. The percentage of wheat area represented in 1997 was higher than in 1990 because of the inclusion of South Africa and all wheat areas of China. Central Asia and the Caucasus states were not included in either survey.

2.2. Methods

ISWYN data were grouped into two periods: the Green Revolution period (1964–1978) and the post-Green Revolution period (1979–1995). All ESWYT data represented the post-Green Revolution period (1979–1999). Yield potential at a particular location in a particular year was represented by the average yield of the top three higher yielding entries at that location and year. Locations were grouped according to ME. Our analysis focused on four spring wheat MEs: two favourable environments (ME 1 and ME 2) and two marginal environments (ME 4 and ME 5).

Wheat yield growth rate (%) for each ME in ESWYT and ISWYN was estimated using the log-linear trend regression

$$\ln(Y) = \alpha + \beta X + \varepsilon$$

where α is the constant; $\ln(Y)$ the natural logarithm of Y, which is the average of the three highest yielding entries per location; X the time (year); and ε the error term. Initially, we included latitude and elevation (in m above sea level) in addition to time (year) in the log-linear regressions to account for location specific effects. However, regression results showed that time had the only consistently significant coefficient. The grouping of locations by ME may have diminished the effects of latitude and elevation on yield; hence, these two independent variables were dropped and only time-trend regressions were used in the analysis.

Yield variability was measured using the Cuddy–Della Valle index, which is the preferred measure of variability for time-series data (Cuddy and Della Valle, 1978; Weber and Sievers, 1985; Singh and Byerlee, 1990). Only ISWYN data were used for this analysis because they covered both the Green Revolution and post-Green Revolution periods. The simple coefficient of variation (CV) tends to overestimate the level of instability in time-series data so it was corrected using the following index:

$$\mathrm{CV} = (\mathrm{CV}^*)(1 - R^2)^{0.5}$$

where CV* is the simple estimate of the CV (%), and R^2 the coefficient of determination from a time-trend regression adjusted by the number of degrees of freedom.

To determine the effects of wheat breeding research on production, wheat production increases during 1990–1997 were estimated using the CIMMYT Wheat Impacts database. Estimated wheat production increase was composed of the sum of: (1) additional area planted to modern wheat varieties in 1990–1997; and (2) yield increases from variety replacement (replacing older modern varieties, MVs, with newer MVs) during the same time period. The formula used for estimating the production increases[1] due to additional area sown to MVs was

$$\Delta Q = (\mathrm{MV}_1 - \mathrm{MV}_0) Y_0 \, \mathrm{e}^{gt}$$

where MV_1 is the area sown to MVs in 1997, MV_0 the area sown to MVs in 1990, Y_0 the yield in 1990, e the exponential term, g the annual rate of yield gain, and t the time period (1990–1997). The rates of gain in yield (g) used in the estimation of production increases were based on the wheat growth rates obtained in the analysis of both ESWYT and ISWYN data. Some may argue that direct translation of experimental yield gains into industry yield gains no longer track yields very well in different wheat growing environments (see Alston et al., 1995; Heisey et al., 2002). However,

[1] In estimating the production increase due to modern wheat area expansion, South Africa and China were excluded to avoid biased estimates. It was only in the 1997 survey that all wheat areas of these two countries were included.

experimental yield gains were used in our estimation of production increases because no long-term globally distributed farm-level data were available.

In the estimation of production increases due to replacement of older MVs with newer MVs, a replacement factor (r) was first calculated based on variety turnover. Yield increases from variety replacement were estimated by applying the formula:

$$\Delta Q = \mathrm{MV}_1 \, rY_0 \, \mathrm{e}^{gt}$$

where MV_1 is the area sown to MVs in 1997, r the replacement factor (based on variety turnover),[2] Y_0 the wheat yield in 1990, e the exponential term, g the rate of yield gain, and t the time period. Factors affecting the rate of variety replacement in wheat were discussed in several studies (Heisey and Brennan, 1991; Heisey, 1990; Alemu et al., 1998; Regassa et al., 1998). An aggregate assessment was made of the relative contribution of favourable and marginal environments to the estimated global wheat production increases during 1990–1997. Note, however, that research costs were not covered in this paper.

3. Results and discussion

3.1. Growth in wheat yield potential

How do trends in wheat yield potential compare in favourable and marginal environments? Analysis of the ISWYN data (1964–1995) shows that there has been a dramatic difference in the rate of growth in yield potential between favourable and marginal environments in the post-Green Revolution period. The rate of the growth in yield potential in favourable wheat growing environments was steady at around 1% per annum during the Green Revolution (1964–1978) and the post-Green Revolution periods (1979–1995), while wheat yield potential in marginal environments grew at double (or more than double) the rate of growth in favourable environments during the post-Green Revolution period. Growth rates in wheat yield potential in ME 4 and ME 5 were 2.75% (70.5 kg/year) and 2.5% (72.3 kg/year), respectively (Table 2).

Yield trend analysis using ESWYT data provide further validation of ISWYN results presented above. Wheat yields in ME 4 grew by about 3.5% per year (approximately 88 kg/year), the highest of the four MEs (Table 3). In ME 5, wheat yield potential grew by a rate of 2.1% per year (46 kg/year). On the other hand, ME 1 and ME 2 sustained growth rates in wheat yield potential of about 1% per year (53.5 and 62.5 kg/year, respectively).

The above findings are consistent with results of a recent analysis (Trethowan, 2001) of progress in improving wheat yields in low- and intermediate-yielding environments, based on data from the Semi-Arid Wheat Yield Trial (SAWYT). Low-yielding environments were defined as those with wheat yields of less than 2.5 t/ha; intermediate-yielding environments had wheat yields of 2.5–4.5 t/ha. In low-yielding environments, the rate of progress in improving wheat yields (expressed as 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 increased from 16 to 45% over the same period. These results imply that, regardless of which data (ESWYT, ISWYN or SAWYT) is used in the analysis, wheat yield potential increased markedly in marginal environments. Care must be taken in using these results, however, because in absolute levels, even in experiments, yields in marginal environments are still much lower than in the favourable areas. However, the increase in average yield potential and the rapid wheat yield growth rates seen in marginal environments indicate enormous potential for improving wheat productivity in those areas.

3.2. Changes in wheat yield variability

Since variability in crop yields is associated with production instability, higher wheat yield variability would imply greater instability. Estimates of variability, however, show an observable drop in yield variability in both drought prone environment ME 4 and high temperature environment ME 5, which indicates improved production stability over time in germplasm

[2] Variety turnover was measured using the age of varieties in farmers' fields. This was estimated by determining the difference between 1997 and the year of release of wheat varieties planted in each of the MEs, and then weighting it by the percentage of (total) area planted to each variety. If the weighted age of the variety (or variety turnover) is 1, the replacement factor (r) is 1; if the variety turnover is 2 years, then r is 0.5, and so on.

Table 2
Rate of growth of wheat yield, ISWYN[a], 1964–1995

Period	ME 1[b] (irrigated)	ME 2 (high rainfall)	ME 4 (drought prone)	ME 5 (high temperature)
1964–1978	1.22 (71.6)[c]	1.72 (81.5)	1.54 (32.4)	1.41 (34.9)
1979–1995	1.32 (84.6)	1.71 (92.8)	2.75 (70.5)	2.53 (72.3)

[a] International Spring Wheat Yield Nursery.
[b] Mega-environment.
[c] Figures in parenthesis are growth in kg/year.

Table 3
Trends in wheat yield growth rate by ME, Elite Selection Wheat Yield Trial, 1979–1999

ME	Growth rate (% per year)	Growth (kg/year)
ME 1: irrigated	0.82	53.5
ME 2: high rainfall	1.16	62.5
ME 4: drought prone	3.48	87.7
ME 5: high temperature	2.10	46.1

developed for these environments (Table 4). This could have resulted from the release of wheat germplasm with yield and input responsiveness combined with tolerance to abiotic stresses. Using ISWYN data, the variability in wheat yields in ME 4 declined by 38.1% from 1964–1978 to 1979–1995. Table 4 also shows that the coefficient of yield variability dropped by 28.3% in ME 5. In contrast, the coefficient of yield variability in both irrigated ME 1 and high rainfall ME 2 environments increased slightly from 1964–1978 to 1979–1995.

The decline in variability in wheat yields in marginal environments confirms an earlier finding (Singh and Byerlee, 1990) using time-series country-level data for 57 countries over 35 years (1951–1986). Results showed a 9 and 16% drop in the coefficient of variability in dryland temperate and tropical wheat environments, respectively, from 1951–1965 to 1976–1986. It is evident that in the post-Green Revolution period, wheat yields in marginal environments became less variable relative to those in favourable areas.

3.3. Production impacts of shifting the yield frontier for marginal environments

There are two sources of production increases from wheat breeding research: the expansion of MV area in marginal environments (the area expansion effect) and the replacement of older MVs with newer ones (the yield effect). Due to limited data availability, the assessment of production impact was performed for 1990 and 1997 only, using the CIMMYT Wheat Impacts database. As mentioned earlier, South Africa and all wheat areas of China were excluded from the estimation of production increases. More than 37 Mt of additional wheat was produced in the developing world in 1997 compared to 235 Mt in 1990 production. Of the increased production in 1997, about 10 Mt—roughly a quarter—came from marginal wheat production environments.

The additional wheat production attributable to MV area expansion effect was about 22 Mt (Table 5). The area expansion effect was very high in both ME 1 (10 Mt) and ME 4 (9.5 Mt). There was a production

Table 4
Changes in the variability of wheat yields in favourable and marginal environments, ISWYN, 1964–1995

ME	CV around trend (%)		Percentage change in CV from 1964–1978 to 1979–1995
	1964–1978	1979–1995	
ME 1: irrigated	27.0	27.1	0.2
ME 2: high rainfall	26.1	26.9	3.1
ME 4: drought prone	25.5	15.8	−38.1
ME 5: high temperature	24.0	17.2	−28.3

Table 5
Production increase (decrease) due to modern variety (MV) area expansion (reduction) and variety replacement by ME, 1990–1997

ME	MV area expansion	MV replacement (Mt)	Total production increase (decrease)
ME 1: irrigated	10.0	9.9	19.9
ME 2: high rainfall	3.8	3.7	7.5
ME 4: drought prone	9.5	1.2	10.7
ME 5: high temperature	(1.5)[a]	0.6	(0.9)
Total production increase	22.0	15.4	37.4

[a] Production loss due to decrease in total wheat area planted in 1997.

loss in ME 5, however, because MV area diminished as a result of reduced total wheat area in Sudan in 1997. While we should have expected a decrease in developing country wheat area due to declining international wheat prices, continued domestic protection of wheat sectors in many countries led to the observed expansion.

On the other hand, the yield effect or additional wheat production from replacement of older MVs with newer MVs in 1997 was 15.4 Mt. Of this, 13.6 Mt came from favourable MEs (Table 5). The unfavourable or marginal MEs contributed 1.8 Mt (1.2 Mt from drought prone ME 4). These increases concur with Byerlee's (1994) finding that the release of newer generations of MVs in areas already sown to MVs—particularly favourable environments such as ME 1 and ME 2—has contributed significantly to productivity growth. However, the relatively low yield

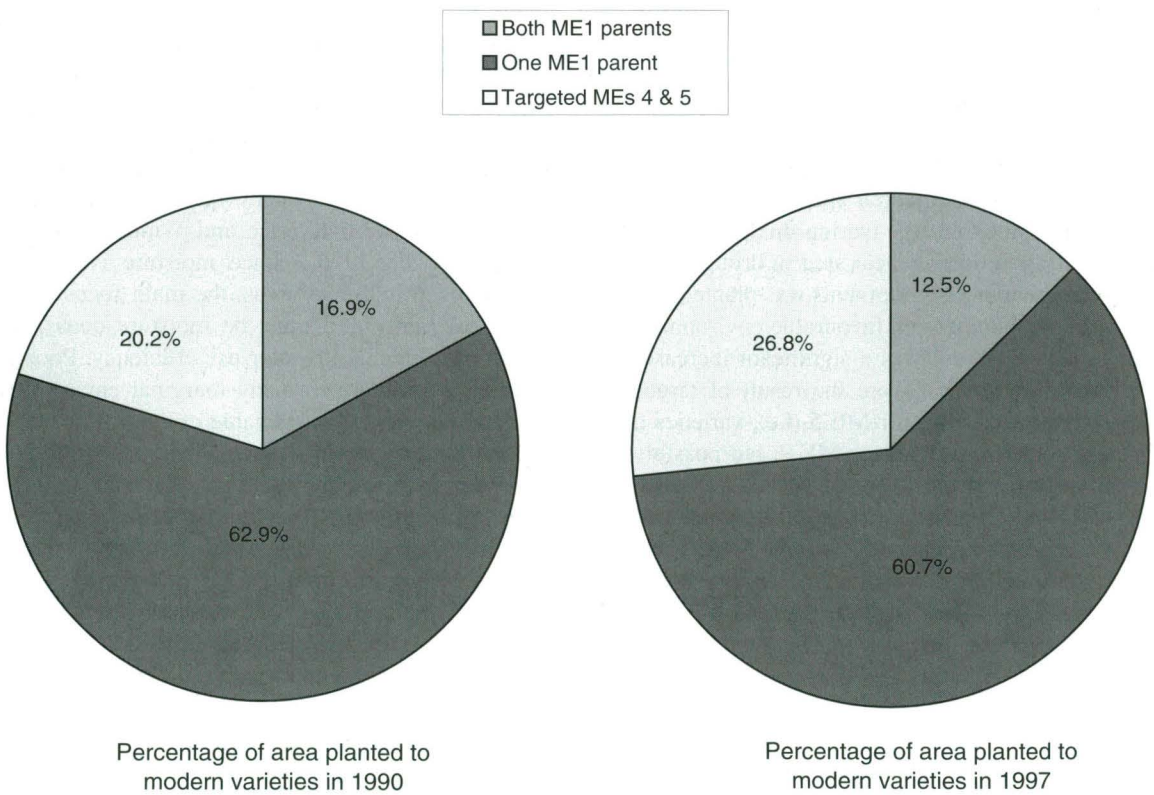

Fig. 1. ME 1 and ME 2 crossover and spill-overs on growth in wheat yield potential in ME 4 and ME 5, 1990 and 1997.

effect for marginal environments may be associated with the very slow rate of variety replacement in many developing countries (see Byerlee and Moya, 1993; Heisey et al., 2002). On average, variety turnover in favourable environments was 3 years faster than in marginal environments. Another reason for the relatively low yield effect for marginal environments is that area expansion during this period was much more important than varietal replacement in most marginal areas.

Both varietal crossover and research spill-overs have influenced the rising production trends in marginal environments. While crossover can be a type of spill-over, we distinguish between the two in this paper. A crossover occurs when a variety with both ME 1 or ME 2 parents (obviously bred for favourable environments) is planted in either ME 4 or ME 5. On the other hand, a spill-over occurs when a variety developed for ME 4 or ME 5 has one ME 1 or ME 2 parent. In other words, spill-overs occur when ME 1 or ME 2 varieties are used in crosses with varieties of other origins. In 1997, crossover varieties from ME 1 and ME 2 occupied 12.5% (about 2 million ha) of the MV area planted in ME 4 and ME 5. There was a 5% decrease in the proportion of area under crossover varieties between 1990 and 1997 (Fig. 1).

On the other hand, the percentage of area under varieties resulting from research spill-overs was about the same in 1990 and 1997. During this period, more than 60% of the modern wheat area in drought prone and high temperature environments was planted to varieties with one parent from favourable environments. By the late 1990s there was a significant increase in area under varieties that were the result of targeted breeding efforts for ME 4 or ME 5 (i.e., varieties did not have parents from ME 1 or ME 2, but possibly a grandparent or great grandparent), from 20% in 1990 to nearly 27% in 1997 (Fig. 1). It is likely that some crossover varieties had been replaced by specifically targeted ME 4 or ME 5 varieties in 1997.

4. Conclusions

Great progress has been made since the Green Revolution in shifting the yield frontier of marginal wheat production environments, particularly in drought and high temperature environments. In the past two decades, the rate of yield gains in these environments was twice that of favourable environments. Yield variability in marginal environments has also declined notably since 1979, while it has increased slightly for favourable environments. Although initial gains resulted from crossover of varieties from favourable environments, targeted breeding efforts have contributed significantly to more recent productivity growth in marginal environments.

Increased production from marginal environments accounted for around 25% of the total wheat production increase in 1997 compared to 1990. New areas under MV wheat production accounted for most of the increase, although within existing wheat producing areas, the slow rate of replacement of older varieties with newer, higher yielding varieties dampened the overall production impact of new cultivars with enhanced stress tolerance. Infrastructure and institutional constraints to accessing new seed and other agricultural technologies continue to be a major stumbling block to rapid productivity growth in marginal lands.

Although improved varieties will play an important 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 (see Bolton, 1979; Byerlee and Winkelmann, 1981; Sanders et al., 1996). 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 to reconstruct poor soils (Bosemark, 1993). Diversification of crops and cropping systems is also important to improve and/or sustain incomes in marginal environments, and research must take this requirement into consideration.

In terms of research resource allocations, however, it is premature to favour one environment over others simply because this paper did not cover research costs. At different times and under different levels of investments, marginal returns to wheat breeding research for favourable and marginal environments may be very

different. Furthermore, Renkow (2000) points out that since no easy generalisations can be made based on available evidence related to the debate on optimal allocation of agricultural research, there is greater need for the review of alternative policies and investment strategies on a case by case basis.

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