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MODERN VARIETIES, PRODUCTIVITY, AND SUSTAINABILITY

Recent Experience and Emerging Challenges

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Modern Varieties, Productivity, and Sustainability: Recent Experience and Emerging Challenges

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Contents

Abstract

The contribution of modern varieties of the three major cereal crops.(rice, wheat, and maize) in the post-Green Revolution period, especially during the past decade or so, is reviewed in light of recent changes in the technical, economic, and institutional environment in which agricultural development strategies are being framed. Particular emphasis is given to the interactions of MVs with input intensification, input efficiency, and sustainability.

Modern varieties have made important contributions toward a sustainable agriculture, both indirectly, through the adoption of land-saving technologies, and directly, through the more efficient use of external inputs and the increased stability of production in many post-Green Revolution areas. There are additional opportunities for MVs to promote greater nutrient use efficiency and to complement the adoption of sustainable practices, such as conservation tillage. Hybrids and the new tools of biotechnology will not lead to a sharp departure from the steady progress in genetic gains achieved over the past two decades through conventional breeding, but the new biotechnologies promise to enhance pest resistance and yield stability of MVs, and thus will contribute toward a more sustainable agriculture.

Economic and institutional issues in restructuring plant breeding programs for the most efficient use of resources, in both the public and private sectors at the national and international level, are reviewed. Three trends suggest a need to consolidate plant breeding programs and analyze the comparative advantage of international and national agricultural research programs at different stages of development in various kinds of research: 1) growing evidence that some biological technologies are internationally transferable and that there are significant economies of size in plant breeding; 2) growing scarcity of resources for agricultural research in both NARSs and IARCs; and 3) growing demands on agricultural researchers to address environmental issues. Outside the commercial agricultural areas of developing countries, the public sector will retain a leading role in plant breeding research and the activities that support it, including biotechnology. Nonetheless, there are opportunities for greater complementarities between private and public sector research that can contribute to more efficient use of research resources in the future.

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Modern Varieties, Productivity, and Sustainability: Recent Experience and Emerging Challenges

Derek Byerlee

Much has been written about the successes and failures of the modern varieties (MVs) that spearheaded the Green Revolution in rice and wheat.[1] Increases in productivity resulting from the widespread adoption of MVs have been well documented, and the implications of this agricultural transformation for alleviating poverty and, more recently, for the health of the environment, have been endlessly debated. Although misleading stereotypes of the Green Revolution still abound in the literature, the purpose of this paper is not to revisit the Green Revolution. Rather, this paper focuses on the contribution of MVs in the post-Green Revolution[2] period, especially during the past decade or so, and identifies challenges for maintaining the momentum in the future through the application of plant breeding in association with the new biotechnologies to develop newer generations of MVs.

It is appropriate to review the role of MVs in light of recent changes in the technical, economic, and institutional environment in which agricultural development strategies are being framed. Interest in the development community has clearly switched from the "high payoff input" approach (Schultz 1964, Hayami and Ruttan 1985), based on MVs and the use of external inputs, to a broader concern for sustainable agriculture, including reduced reliance on external inputs. Yet as this paper will show, the continued development and diffusion of MVs offers a proven record of not only increasing productivity but also of directly or indirectly contributing to a more sustainable agriculture.

In post-Green Revolution agriculture, genetic gains in yield and improvements in other varietal traits contribute perhaps half of all gains in productivity (Duvick 1991, Coffman and Bates 1993, Evans 1993, Evenson and Rosegrant 1993). In addition, investment in plant breeding, to the extent that it offers ways of substituting for the use of external inputs or complementing changes in practices to conserve natural resources, is in itself an important vehicle for directly promoting a more sustainable agriculture.

It is also appropriate to re-examine the role of plant breeding research in increasing productivity and *sustainability* given that resources devoted to agricultural research have declined sharply in recent years. Commodity research programs in national agricultural research systems (NARSs) as well as in international agricultural research centers (IARCs) are facing critical budgetary shortages which demand rationalization of the size, number, and location of plant breeding programs. At the same time, the increased emphasis on privatization in all sectors of the economy and the growing use of intellectual property rights (IPRs) for biological innovations, including MVs, raise the issue of the future role of the private sector in developing and diffusing MVs.

Against this background, this paper first provides a brief update on the diffusion of MVs for the three major cereal crops (rice, wheat, and maize) and identifies constraints on further diffusion of MVs to areas where they have not yet been adopted.[3] While it is true that rice, wheat, and maize production are concentrated in the medium- and high-potential production environments of the developing world, these crops dominate world food production (accounting for 50% of the calories consumed globally, and 57% in developing countries[4]) and are critical to food security, sustaining the resource base, and alleviating poverty.

A second broad objective of this paper is to highlight the important contributions of MVs in the post-Green

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1 The term "modern varieties" (MVs) used in this paper refers to semidwarf varieties of rice and wheat and to high yielding, input responsive and generally short-statured maize varieties or hybrids developed since 1960. Since some of these varieties are now more than 30 years old, the term "modern" is somewhat of a misnomer, but it is preserved here to maintain consistency with previous publications on the subject.

2 "Post-Green Revolution" refers to the period after the first generation of MVs was widely adopted. In advanced areas, such as the Indian Punjab or Central Luzon, this period dates from the early 1970s.

3 See Dalrymple and Srivastava (1994) for a recent review of the *transfer* of MV technology for these crops. This paper focuses on the *development* of MV technology.

4 Including a small share of calories from indirect consumption of maize and wheat as feed grains.

Revolution period and their interactions with input intensification, input efficiency, and sustainability. A third objective is to review opportunities for MVs to contribute to further increases in productivity and to sustaining the resource base, with particular emphasis on the use of hybrid seed and the potential of the new biotechnologies. Finally, the paper outlines emerging economic and institutional issues in restructuring plant breeding programs to use resources more efficiently in the public and the private sector at the national and international level.

Modern Varieties in a Stylized Sequence of Technical Change

Elsewhere I have defined a sequential process that characterizes technical change in many settings, both in irrigated areas where the Green Revolution had its initial success as well as more recent changes in rainfed agriculture (and indeed in the industrialized countries) (Byerlee 1992). These stages can be summarized as follows:

1. A *Green Revolution Phase* when MVs become available and, together with the adoption of modest levels of external inputs, enable a dramatic jump in productivity.

2. A *First Post-Green Revolution* or *Input Intensification Phase* when farmers move toward improved *allocative efficiency* by increasing the level of use of external inputs toward their economic optima.

3. A *Second Post-Green Revolution* or *Input Efficiency Phase* when farmers move toward increased *technical efficiency* by using available inputs more efficiently (that is, greater output for a given level of input use) and at the same time contribute to sustaining the resource base.

These stages summarize reasonably well many technological transformations in agriculture, beginning with hybrid maize in the USA (Byerlee and López-Pereira 1994), continuing with the Green Revolution in rice and wheat in irrigated cropping systems of Asia (Byerlee 1992), and including more recent changes in rainfed cropping systems, such as maize-based systems in Africa (Byerlee and Heisey 1993).

Modern varieties play a key role in each of these phases of change. They have been most closely associated with the Green Revolution phase, for it was the adoption of new plant types, interacting closely with changes in crop management (especially improvements in soil fertility and water supply), that provided the basis for rapid productivity increases. In the first post-Green Revolution phase, the original MVs have been replaced by newer generations of MVs that allow continued gains in productivity as well as stability in the face of evolving pest biotypes. Modern varieties may make a similar contribution in the second post-Green-Revolution phase, as well as facilitate the movement toward input efficiency, through:[5]

- Development of nutrient-efficient or pest-resistant MVs that substitute for the use of external inputs, such as chemical fertilizers or pesticides.

- Development of MVs that facilitate the adoption of resource-conserving technologies — for example, varieties resistant to diseases promoted by crop residues left as ground cover in conservation tillage, or shade-tolerant varieties that facilitate the adoption of alley cropping.

- Development of MVs that reduce the environmental cost of particular practices, such as a variety resistant to an environmentally benign herbicide that can substitute for more toxic herbicides.

Input efficiency embodied in MVs will usually require fewer technical skills and less management on the part of farmers than alternative approaches. For example, a variety resistant to a particular pest generally will be easier to diffuse to farmers, and easier for farmers to use effectively, than integrated pest management methods (IPM) that tailor pesticide use to quantitative estimates of pest and predator populations. Moreover, it must be recognized that pest-resistant varieties typically form an important component of IPM strategies.

Thus the contribution of MVs will evolve over time to fit changing needs at different stages of development. Nonetheless, for simplicity this paper will follow Morris, Dubin, and Pokhrel (1994) in distinguishing two broad types of varietal change:

[5] Although earlier generations of MVs already may incorporate many of these traits, emphasis on input efficiency through plant breeding has increased in recent years.

- *Type A varietal changes,* when MVs first replace old varieties (either traditional or older improved varieties, "TVs"), and enable a sharp break in the rate of productivity growth. This type of varietal change corresponds to the Green Revolution phase and has been extensively analyzed in the literature (e.g., Lipton with Longhurst 1989).
- *Type B varietal changes,* when newer generations of MVs periodically (at least once a decade) replace the original MVs, and the subsequent impacts of changing varieties are usually evolutionary rather than revolutionary. This type of varietal change characterizes the post-Green Revolution phases emphasized in this paper.

The Spread of MVs and Input Intensification: A Brief Update

Adoption of MVs: The Current Situation

The adoption of MVs which began in the 1960s has progressed steadily over the past three decades, at least for the three major cereal crops.[6] Currently almost 70% of the combined rice, wheat, and maize area in developing countries is planted to MVs. Table 1 shows that the process has gone furthest in wheat and rice. In the case of spring bread wheats, which account for over two-thirds of developing world wheat production, MVs are now sown on 85% of the area, and account for an estimated 93% of production in developing countries (Byerlee and Moya 1993). While the popular perception is that the Green Revolution in wheat was a revolution in irrigated areas, over the past 10-15 years most of the expansion in area under MVs of wheat (over 16 million ha) has occurred in rainfed areas, beginning first with wetter areas and proceeding gradually to drier areas (Figure 1). In rice, too, the trend over the past two decades has been toward diffusion of MVs in less favorable environments, although the process is still very incomplete (Hayami and Otsuka 1994, David and Otsuka 1994, Adesina and Zinnah 1993, Upadhyaya et al. 1993). Finally, the adoption of MVs in maize has grown steadily to reach over half of the total maize area in developing countries. Significantly, maize is the single success story for the diffusion of MVs in sub-Saharan Africa, where rice and wheat are generally not important food staples (Byerlee and Heisey 1993, Smale and Heisey 1994).

The remaining areas where MVs are not widely grown possess one or more of the following characteristics:

- *Areas generally classified as marginal for crop production.* There have been some notable successes in developing MVs capable of tolerating soil stresses, especially MVs that perform well under acid soil conditions in Latin America (Byerlee and Moya 1993, Granados, Pandey, and Ceballos 1993, Rao et al. 1993). However, MVs have not been adopted widely in areas where drought stress is frequent or, in the case of rice, in areas where water control is very poor. Table 2 summarizes patterns in the diffusion of rice and wheat MVs with respect to moisture status. (The prospects for overcoming constraints to diffusion of MVs in marginal areas will be discussed in greater detail below).
- *Areas with very poor infrastructure and no access to markets.* These problems commonly affect maize, especially in the relatively land-

Table 1. Percent area planted to modern varieties of rice, wheat, and maize in developing countries, 1970-90

	Rice[a]			Wheat[a]				Maize
	1970	1983	1991	1970	1977	1983	1990	1990
Sub-Saharan Africa	4	15	na	5	22	32	52	43
West Asia/North Africa	0	11	na	5	18	31	42	53
Asia (excluding China)	12	48	67	42	69	79	88	45
China	77	95	100	na	na	na	70	90
Latin America	4	28	58	11	24	68	82	46
All developing countries	30	59	74	20[b]	41[b]	59[b]	70	57

Source: For rice, Anderson, Herdt, and Scobie (1986), IRRI (pers. comm.), CIAT(pers. comm); for wheat, Byerlee and Moya (1993); for maize, Byerlee and López-Pereira (1993).

a Excludes tall varieties released since 1965. If these varieties are included, the area under MVs increases, especially for rice in Latin America.

b Excludes China.

6 Significant progress has also been made in diffusion of MVs of other crops. For example, nearly half of the area of sorghum and millet in India (almost all rainfed) is now sown to MVs.

extensive systems of Africa and in hillside systems of Latin America. Also, unlike seed of modern wheat and rice varieties, which is largely diffused from farmer to farmer, seed of modern maize varieties is difficult to disseminate without an efficient system for producing and marketing seed. This is of course particularly true of hybrid maize, but recent evidence suggests that open-pollinated varieties of maize diffuse poorly from farmer to farmer because maize is a cross-pollinating crop, and seed quickly becomes genetically mixed (Longmire and Mohammed 1994, Byerlee and López-Pereira 1994).

- *Areas where quality traits outweigh the yield advantages of MVs.* For example, until recently the adoption of MVs of rice in Thailand was low because the price discount for available MVs more than offset their yield advantage (Herdt and Capule 1983). When MVs with quality traits comparable to those of TVs have been developed, the MVs have been adopted rapidly. A high-quality modern rice variety was almost completely adopted in Pakistan within three years after its release in the mid-1980s (Sharif et al. 1992). A similar situation has prevailed for hybrid maize in Malawi, where new flint maize varieties, whose characteristics are preferred for local processing, have been well accepted by farmers (Smale and Heisey 1994).

- *Areas where other varietal traits have a high value to farmers.* In many marginal areas and in very isolated areas with poor infrastructure, the value of crop by-products such as straw (valued both for yield and quality) may sometimes be an overriding factor in variety selection. Traxler and Byerlee (1993) relate the adoption of MVs of wheat in some areas to this trait; Kelly, Rao, and Walker (1991) find similar evidence that high fodder values have inhibited the adoption of modern sorghum varieties in dry areas of India.

- *Areas where the research system has been unable to produce varieties possessing a yield advantage.* While less common today, this situation is still largely true of some areas with little or no local research

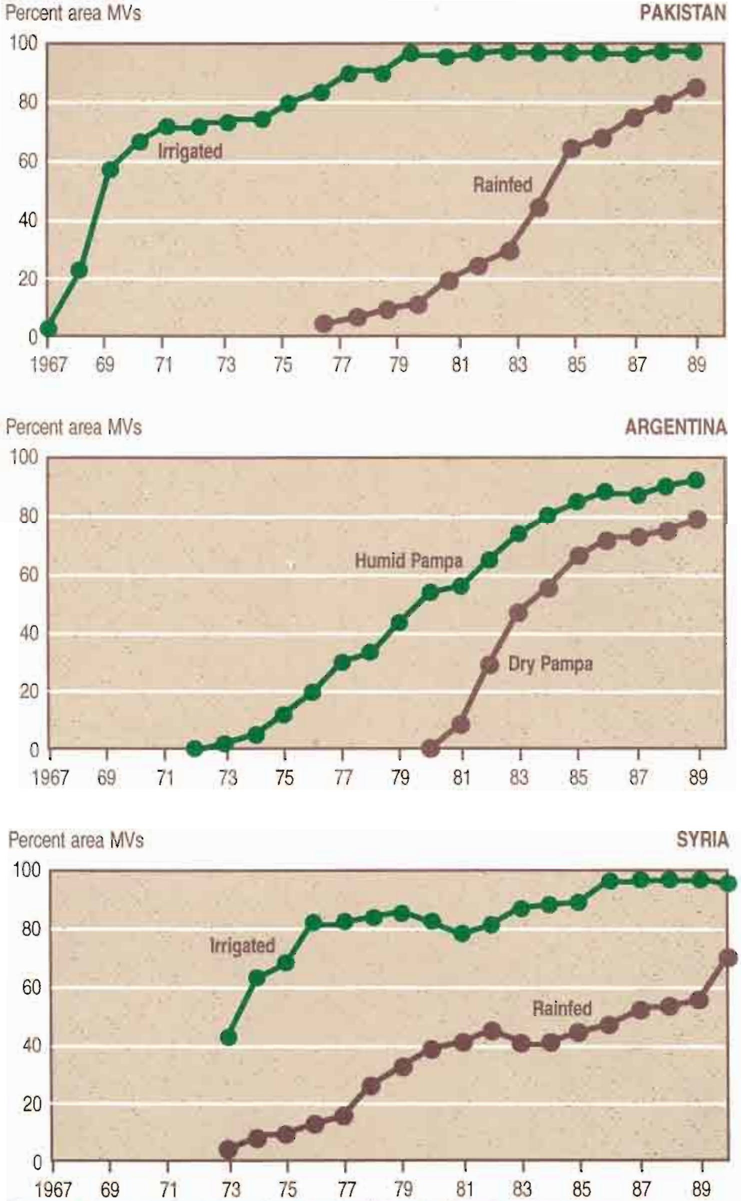


Figure 1. Adoption of modern spring wheat varieties in different moisture zones.
Source: Byerlee and Moya (1993).

capacity (e.g., some parts of Africa) and areas where local varieties have high yield potential as well as other desirable traits (e.g., the highland maize areas of Mexico).

The Spread of MVs to Marginal Areas

This update on the diffusion of MVs clearly indicates that, at least for rice and wheat, the further spread of MVs depends on success in developing varieties suitable for marginal areas, especially areas defined as marginal because of moisture stress or poor water control.[7] This raises important questions about the roles and limitations of MVs in marginal areas, and about the relative emphasis to give to marginal areas in plant breeding strategies in the future. The case of dryland wheat serves to illustrate these issues (Byerlee and Morris 1993).

- There is little doubt that the yield advantage of MVs of wheat over TVs was sharply higher in irrigated areas (about 40%) than in the higher rainfall areas (about 15-25%) and low rainfall areas (usually not more than 10%) where MVs were subsequently adopted. If drought is the main factor characterizing marginal areas, breeding progress will be slower in both an absolute and relative sense.[8] Some argue that slow progress in breeding for drought conditions reflects the breeding approaches employed, which emphasize selection under high-input conditions (Simmonds and Talbot 1992, Ceccarelli 1989). However, there is little evidence that a radical change in breeding approach will lead to a breakthrough in developing MVs for marginal dryland areas. Indeed, there is considerable evidence that MVs developed by conventional breeding approaches yield better than TVs under many low-input conditions (Lipton with Longhurst 1989). At the same time, even in countries such as Australia that have strong plant breeding programs targeted at very dry production environments, progress has been slow (Byerlee and Moya 1993).

- Although MVs offer limited prospects for improving productivity in dryland marginal areas, substantial productivity gains can often be achieved through crop and resource management to conserve and utilize moisture more efficiently (e.g., Morris, Belaid, and Byerlee 1991, Sanders 1989). Thus the sequence of change described above, in which MVs are the lead technology, is not very relevant to most marginal areas. In some marginal areas, improved technology of *any* kind may not be the most efficient change agent; other investments, such as development of small dams, or even investments that encourage nonagricultural activities, such as infrastructure or schooling, may be more appropriate.

- Because the yield advantage of MVs is lower in marginal areas, other varietal traits discussed above (e.g., grain quality and the quantity and quality of crop by-products) assume greater importance, especially since market development in many marginal areas is poor. In irrigated areas the higher yields of MVs and their earlier maturity, which enabled increased cropping

Table 2. Adoption of modern varieties and share of production by moisture regime, rice and wheat, mid-1980s

Rice			Wheat		
Environment	Percent total production	Percent area MVs	Environment	Percent total production	Percent area MVs
Irrigated lowlands	71	95	Irrigated	49	91
Rainfed lowlands	19	40	Rainfed (>500 mm)[a]	28	60
Deepwater	7	0	Rainfed (300-500 mm)[a]	22	45
Upland	4	0	Rainfed (<300 mm)[a]	1	21
Total	**100**	**48**	**Total**	**100**	**62**

Source: IRRI (pers. comm.), Byerlee and Morris (1993), CIMMYT data files, and CGIAR/TAC (1993).
a Rainfall immediately prior to and during the growing season.

7 A similar pattern is seen for sorghum and millet in India, where much of the area in the medium rainfall zones is now planted to improved varieties (Kelly, Rao, and Walker 1991, Pray, Mueller, and Ribeiro 1991).

8 Slower progress in breeding for marginal areas has also been observed in industrialized countries (e.g., Perry and D'Antuono 1989). Recently a number of observers have advocated more participatory approaches to plant breeding for marginal areas and small farmers, by involving farmers directly in varietal selection to ensure that varieties meet farmers' criteria (Sperling, Loevinsohn, and Ntambovura 1993; Berg et al. 1991; Haugerud and Collinson 1990; Simmonds and Talbot 1992; Maurya, Bottrall, and Farrington 1988).

intensity, easily compensated for the 15% price discount on MVs of wheat that was common in those areas. However, in marginal areas, where the yield advantage of MVs may only be 10%, such a discount for quality will limit adoption. Thus although "crossovers," in which TVs outyield MVs at low input levels, may not be very common when only grain yield is considered (Lipton with Longhurst 1989), they may be quite important when the total economic value of production, defined in terms of grain quality and crop by-products, is taken into account (Smale et al. 1991, Traxler and Byerlee 1993, Wijeratne and Chandrasiri 1993).

- Despite frequent assertions to the contrary, there is little evidence that IARCs and NARSs have underinvested systematically in breeding research for marginal areas. A recent analysis of resource allocations in wheat breeding in CIMMYT and India found that there may actually be over-investment in research for marginal areas, even when equity as well as efficiency criteria are accounted for in the allocation of research resources (Byerlee and Morris 1993). Similar trends have been observed for rice; resources allocated to marginal rice environments, including uplands and deepwater rice areas, are high relative to their importance in rice production (CGIAR/TAC 1993).[9] In both cases, marginal production environments constitute only a small share of total production (Table 2).

- Finally, there is evidence of spill-overs of the benefits of technical change in favored areas to marginal areas through markets for food grains and labor, since most poor households in marginal areas are net food purchasers and depend increasingly on off-farm sources of income, including remittances of migrant laborers (David and Otsuka 1994, Renkow 1993).

Input Intensification

The intensification of input use, especially water and fertilizer, has been closely associated with the adoption of MVs (see Figure 2 for irrigated wheat and Figure 3 for rainfed wheat). This process of intensification has continued long after the adoption of the first generation of MVs, and only in the most advanced areas (e.g., the Yaqui Valley in Mexico and the Indian Punjab) is input use leveling off as a result of diminishing returns to higher levels of inputs. Increasing input intensification seems to be explained not so much by the release of newer

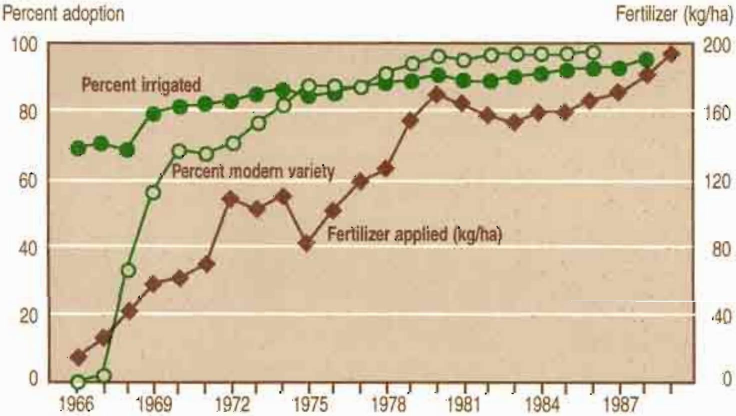


Figure 2. Recent trends in the use of inputs in irrigated wheat production, Punjab, India.
Source: Sidhu and Byerlee (1992).

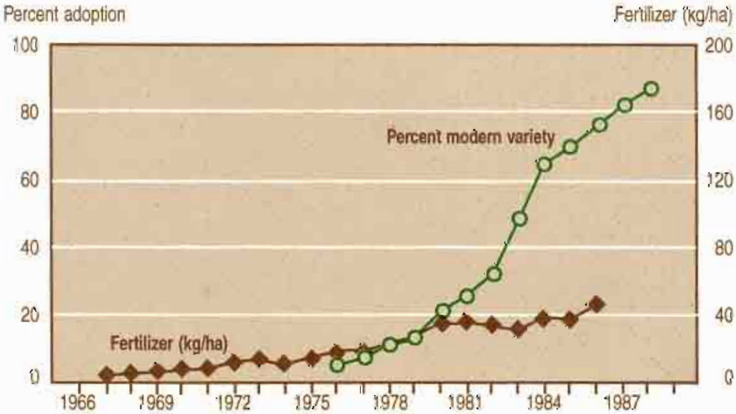


Figure 3. Adoption of improved seed and fertilizer in rainfed wheat, Punjab, Pakistan.
Source: Byerlee and Siddiq (1994).

9 **It is estimated that the two marginal rice growing environments, upland and deepwater rice, account for about 10% of rice production but receive over 30% of the CGIAR expenditures on rice research (CGIAR/TAC 1993).**

and more input-responsive MVs — as hypothesized by Hayami and Ruttan (1985) and Hayami and Otsuka (1994) — but by farmers' accumulation of capital and acquired knowledge, as well as the development of more efficient markets for inputs. For example, the optimum nitrogen level for wheat is less than 10% higher for the recent generation of MVs, released in the 1980s, than it was for the original MVs released in the 1960s (Traxler and Byerlee 1993). In contrast, the level of nitrogen applied to wheat in most post-Green Revolution areas has increased linearly up to the present, more than doubling in the post-Green Revolution period (Byerlee 1992).

Input intensification has also occurred in rainfed areas (Figure 3), although input use is at a lower level than in irrigated areas. In sub-Saharan Africa, where input markets are not well developed, the process of input intensification has been very slow, as exemplified in the very low use of fertilizer in Kenya almost 20 years after the adoption of hybrid maize. Indeed, in the case of maize, the link between MVs and input intensification is weak compared to rice and wheat and reflects local conditions, especially seed and fertilizer markets (Table 3).

Thus input intensification, especially the use of chemical fertilizers, can continue to make important contributions to increasing food production in many areas where MVs have already been adopted. In land-intensive systems with medium to high potential, where fertilizer use remains very low (e.g., many areas of Africa), productivity gains from increased input use will outweigh any environmental costs of using higher levels of inputs.[10] But unlike the initial adoption of external inputs that was associated with the spread of MVs, input intensification in these areas now depends much less on interaction with the adoption of newer generations of MVs and more on other factors, such as market and infrastructural development and farmers' experience.

MVs and Productivity Growth in Post-Green Revolution Areas

The Green Revolution was a major stimulus to investment by NARSs in plant breeding research (see later). This is reflected in an increasing number of varietal releases by NARSs over the past 25 years (Figure 4). A large number of these varieties were developed to replace the original

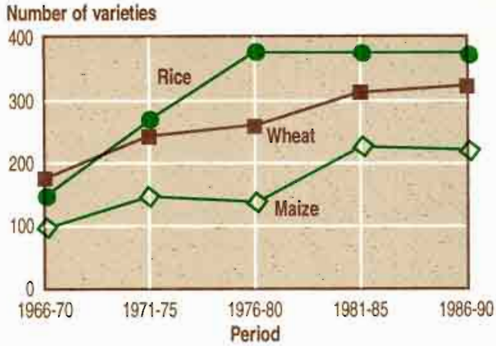


Figure 4. Number of varieties released per five-year period, developing countries (China excluded).
Source: Byerlee and Moya (1993); López-Pereira and Morris (1994); and R. Evenson (pers. comm.).

Table 3. Adoption of improved maize varieties and fertilizer by small-scale farmers, selected developing countries

		Percent adoption		
	Period	Improved varieties/ hybrids	Fertilizer	Source
MV adoption > fertilizer adoption				
Dry regions, Zimbabwe	mid-1980s	100[a]	20[a]	Rohrbach (1989)
Thailand	1990	100[b]	45[b]	Harrington et al. (1991)
Kenya	1993	71[a]	49[a]	R. Hassan (pers. comm.)
Ghana	1990	48[b]	26[b]	GGDP (1991)
Paraná, Brazil	1985	68[b]	46[b]	FIGBE, Censo Agropecuario (1985)
MV adoption < fertilizer adoption				
East Java, Indonesia	mid-1980s	52[a]	100[a]	Krisdiana et al. (1991)
Punjab, India	1992	36[b]	98[b]	Singh (1992)
Eastern Province, Zambia	mid 1980s	36[a]	67[a]	Jha and Hojjati (1993)
Pakistan	1989	26[a]	85[a]	PARC/CIMMYT survey (1990)
Mexico	mid-1980s	26[a]	70[a]	Hibon et al. (1992)
Malawi	1990	18[b]	65[b]	M. Smale (pers. comm.)

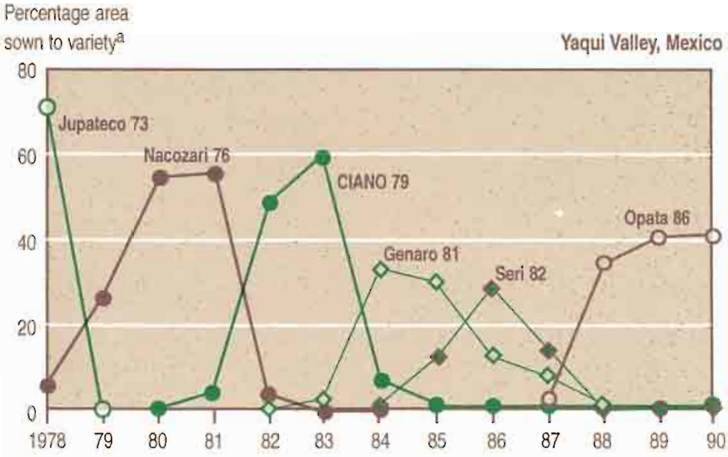
[a] Based on percentage of farmers using practice.
[b] Based on percentage area with practice.

[10] Of course, other approaches, such as organic sources of soil nutrients, which do not depend on the use of external inputs, should also be developed and promoted. However, even if these approaches are applied with success, the use of external sources of nutrients will have to increase (Byerlee and Heisey 1993). The environmental costs of pesticides are generally much higher than for fertilizer and should be weighed against their benefits at an early stage of input intensification.

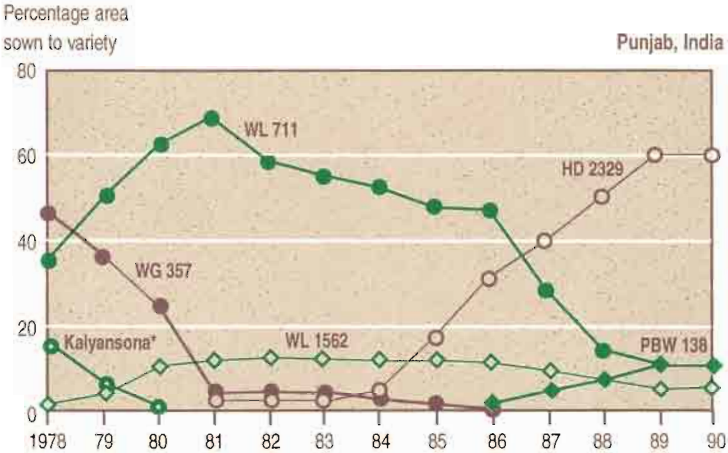
Green Revolution varieties, as breeding strategies became more targeted on specific environments. For example, although only two wheat varieties spearheaded the Green Revolution in India, the Indian national wheat research program now releases an average of eight varieties per year for more than 20 different "recommendation domains," defined in terms of production zone, moisture availability, and planting date (the latter determined by cropping system). Most farmers in post-Green Revolution areas have replaced varieties at least twice since the original adoption of semidwarf varieties in the 1960s — that is, farmers are well established in Type B varietal change, defined above (Figure 5). A similar situation seems to apply to rice in Indonesia, where varieties have become more site-specific and farmers replace varieties every 10 years or less (Pardey et al. 1992, Jatileksono and Otsuka 1993).

Crop breeding programs have multiple goals, although increasing yield potential continues to be the most important objective (Table 4). However, over time, improvements in yield stability (through enhanced pest resistance) and, more recently, improvements in grain quality, have grown in importance as goals of breeding programs.

In the post-Green Revolution era, improved varieties have made a significant contribution to increased productivity through genetic gains in yield. Genetic gains in yield translate into equivalent gains in Total Factor



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



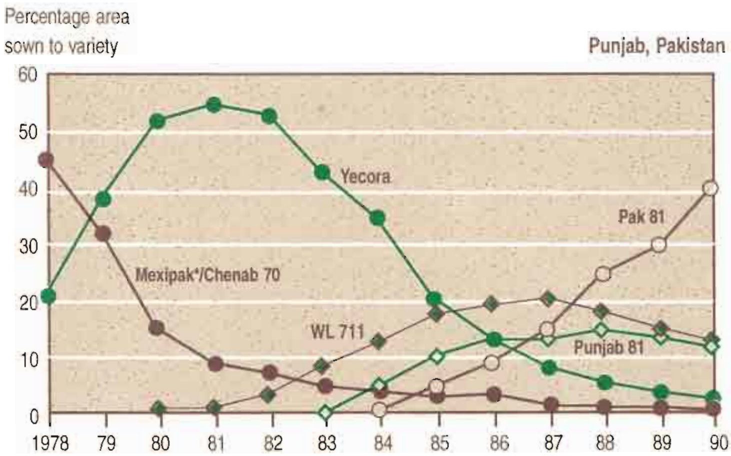


Figure 5. Patterns of wheat varietal change in post-Green Revolution areas of Mexico, India, and Pakistan.

Source: Byerlee and Moya (1993).
Note: * = Green Revolution variety.

Productivity (the ratio of output to the sum of all inputs), provided that farmers are continually adopting the newer varieties. Because no further Green-Revolution-like breakthroughs in yield potential have been achieved (or are likely), the cumulative importance of these incremental gains in yield through Type B varietal change is often overlooked as a source of productivity growth. In the US, for example, the original hybrid maize varieties that were the subject of Griliches' seminal study of the impacts of plant breeding research provided a yield gain of about 15% or about 300 kg/ha (Griliches 1957). However, since the diffusion of the first generation of hybrid maize varieties in the decade after 1933, newer higher yielding hybrids have been released almost annually to provide a linear increase in yields of about 50 kg/ha (Duvick 1992). The cumulative impact of Type B varietal change in maize in the US over the past 50 years (about 2,500 kg/ha) dwarfs the impact of the original adoption of hybrid maize.[11]

Since the first semidwarf wheat varieties were introduced in developing countries, genetic yield gains of 0.5-1.5% annually for MVs of wheat have been well documented (Table 5). Thus in irrigated areas, yield gains in the post-Green Revolution period have cumulatively provided a 20% gain in wheat yields. During the period 1977-90, Type B varietal changes overtook Type A changes as the main source of productivity increases (Table 6), and in irrigated areas they accounted for over 80% of the gains. Together these gains have provided a high return on the investment in national and international wheat improvement research of over 50% annually (Byerlee and Traxler 1994). In rice, the major gains have been made in developing higher yielding, earlier maturing varieties. If yields are measured per day, genetic gains in rice have been at least equal to those achieved in wheat. Finally, genetic gains in maize yields have often been more rapid (Pandey and Gardener 1992), but they have not always been translated to farmers' fields.[12]

In irrigated areas, a further source of genetic gains in productivity in the post-Green Revolution period has

Table 5. Annual rates of genetic gain in wheat yields in different environments over the past two decades, developing countries

Environment and country	Rate of gain[a] (%/year)
Irrigated	
Northwest Mexico	0.6 - 1.1%[b]
Northwest India	0.5 - 1.0[b]
Punjab, Pakistan	0.8[b]
Zimbabwe	1.0[b]
Irrigated hot	
Sudan	0.9[c]
Rainfed	
Brazil	0.5 - 0.8[b]
Paraguay	1.3[c]
Central India	0[c]
Rainfed acid soils	
Brazil	2.2 - 3.2%[c]

a Period varies but most common period is from about 1970 to late 1980s.
b Semidwarf varieties only.
c Includes effect of switching from tall to semidwarf varieties.
Source: Byerlee and Moya (1993).

Table 4. Relative priority given to breeding objectives in rice, wheat, and maize

Objective	Rice, 1984 (% of total)[a]	Spring wheat, 1992 (% of total)[b]	Tropical maize, 1990 (% of total)[c]
Yield potential	93	92	96
Grain quality	78	58	42
Maturity	72	65	44
Disease resistance	60	85	67
Insect resistance	46	25	32
Drought tolerance	19	58	29
Cold tolerance	14	33	3
Heat tolerance	na	48	na
Soil acidity and salinity	na	12	13

Source: Based on Hargrove, Cabanilla, and Coffman (1988), Bohn and Byerlee (1993), Pandey and Gardner (1992), and S. Pandey (pers. comm.).
na = not available.
a Based on percent of crosses made with a given trait as an objective. Survey of 30 breeding programs.
b Based on breeders' ranking of priorities from highest (100%) to lowest (0%). Survey of 66 breeding programs.
c Based on percent of breeders who consider the trait important. Survey of 48 breeding programs.

11 In practice it is difficult to separate gains in yield potential from the effects of interaction with increased plant density and higher doses of nitrogen fertilizer. Also, as discussed later, the increase in resources invested in maize breeding in the USA has been exponential compared to the linear gains in yields, which implies diminishing returns to investment in maize improvement.

12 For example, after the successes in developing and disseminating hybrid maize in several countries, such as Kenya, Zimbabwe, El Salvador, and India, most programs have not been able to release newer higher yielding hybrids. As a result, maize hybrids used in developing countries tend to be old, often developed over 20 years ago.

been increased cropping intensity, achieved in large part because of the availability of earlier maturing MVs. However, for plant breeders this increased cropping intensity poses tradeoffs between different crops grown in the same system. Throughout the irrigated areas of South Asia, for example, the planting date for wheat in double cropping patterns has grown progressively later due to the intensification of cropping patterns (Byerlee 1992), and genetic gains in yields have been more modest for wheat that is planted late. However, this has been more than compensated by genetic gains in productivity in the crop following wheat, especially in rice and cotton.

In rainfed areas, too, the early maturity of MVs has often been an important factor in their successful adoption in small-farm agriculture. In sub-Saharan Africa, early maturing maize varieties have provided important benefits, because small farmers plant late as a result of draft power and labor constraints. Even when maize is planted on time, early harvests assure farmers a supply of food during the "hungry season" (Haugerud and Collinson 1990).

MVs and Sustainability

The development of MVs is an essential element of sustainable cropping systems (Fischer 1993). Modern varieties can contribute both indirectly and directly to sustaining the resource base. Their indirect contribution — through land-saving increases in productivity and poverty alleviation effects — is often their most important contribution. Productivity increases in favorable areas alleviate pressure to migrate to more marginal environments, which are also often more fragile environments (Harrington 1993). Productivity growth in favored areas may also benefit the poor in marginal areas through lower food prices and greater employment opportunities. To date, these indirect effects have not been sufficiently recognized in the sustainability debate.

Modern varieties may also contribute directly, either positively or negatively, to conservation of natural resources through their interaction with input use and through their effect on biodiversity. In addition, system stability in the face of external shocks is often used as a measure of sustainability (Conway and Barbier 1990). These direct effects of MVs on sustainability are discussed below.

Table 6. 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					
Type A change					
Irrigated	0	0.10	1.94	0.12	2.52
High rainfall	0.09	0.46	0.00	1.09	1.69
Acid soils	0	0.52	0.00	0.40	0.40
Drought	0	0.21	0.13	0.31	0.65
Type B change					
Irrigated	0	0.80	7.43	0.40	8.63
High rainfall	0.06	0.44	0	1.08	1.57
Acid soils	0	0	0	0	0
Drought	0	0	0	0	0
Total production increase, Type A and B, 1990 (Mt)	0.14	2.43	9.50	3.39	15.47
Percent production increase due to Type A adoption	62	49	22	56	34
Total value of production increase, 1990 (US$ 1990, billions)	.03	.51	1.85	.66	3.06

Source: Byerlee and Moya (1993).
a Excludes winter wheats.
b Mt = million metric tons.

Resistance to Biotic Stresses and Maintenance Research

Probably the most underestimated contribution of MVs has been their superior pest resistance. The statement that TVs provided pest resistance superior to that of MVs has been repeated widely in the literature (Cleveland and Soleri 1989, Conway and Barbier 1990, Berg et al. 1991, Hobbelink 1991, Shiva 1991). In fact, prior to the Green Revolution, losses to insects and diseases were often very substantial because TVs had poor resistance. Severe losses to rust diseases of wheat in many environments were a major impetus for the establishment of wheat breeding programs in the colonial period. Prior to the adoption of improved wheat varieties in India in the 1920s and 1930s, the price of wheat in India was significantly correlated with the incidence of weather conditions favorable for the development of rust epidemics in the highly susceptible local varieties (Howard and Howard 1928). The MVs of wheat released in the 1960s built on over 20 years of research in Mexico to incorporate resistance to the major rust diseases (Table 7). In contrast, the first MVs of rice were developed through a crash program and lacked resistance to many important diseases and insects (as did the local varieties they replaced) (Hargrove 1977, Ward 1985).[13] Subsequent research emphasized stability through resistance to multiple pests, so since the late 1970s newer rice varieties have incorporated resistance to six or seven major pests, unlike the Green Revolution varieties, which were resistant to one or two (Khush 1990, Herdt and Capule 1983).

Improved pest resistance contributes to sustainability not only through increased yield stability but also through reduced use of pesticides, which include some of the most environmentally harmful chemicals. The record on pesticide use is variable. In rice, there is no doubt that pesticide use increased rapidly in the Green Revolution period when crop intensification, especially the adoption of continuous year-round rice cropping, exacerbated pest losses. Pesticides in rice environments have had significant negative effects not only on the environment but also on the health of people exposed to the pesticides (Antle and Pingali 1994). However, with the superior pest resistance of newer MVs, the evidence suggests that pesticide application is usually no longer necessary and in fact may speed the breakdown of genetic resistance (farmers continue to apply prophylactic applications, however) (Rola and Pingali 1991). In most of the developing world, pesticide use on wheat has been minimal, and the superior disease resistance of MVs in the developing world has generally substituted for the fungicides that are widely used on wheat in industrialized countries.[14] The superior disease resistance of MVs of wheat is reflected in greatly increased stability of yields in farmers' fields (Singh and Byerlee 1990).

Table 7. Average coefficient of infection for leaf rust and yellow rust in spring wheat at 50 locations

Type of variety	Leaf rust mean coefficient,[a] 1978-81	Yellow rust mean coefficient,[a] 1978-81
Local	35	18
Improved tall	13	8
Semidwarf	8	9

Source: Rajaram, Singh, and Torres (1988).
a The average coefficient of infection is an index ranging from 0 (disease free) to 100 (maximum infection). Scores were taken from an international disease screening nursery grown in most spring wheat producing countries.

An increasing proportion of research resources in plant breeding has been spent to maintain or improve resistance to pests in the face of evolving pest biotypes (Hargrove, Cabanilla, and Coffman 1988, Bohn and Byerlee 1993). Maintenance research (defined as breeding to maintain previous levels of resistance rather than improve pest resistance in terms of degree or durability) is critical to yield stability, as shown in Figure 6 for rice and wheat. A recent survey estimated that 28% of resources invested in wheat breeding research were devoted to this type of maintenance research (Bohn and Byerlee 1993). Of course, such maintenance research is successful only if farmers regularly replace their varieties with newer ones that incorporate the new sources of resistance. In the case of wheat, the expected longevity of rust resistance in important production environments is about seven years. In areas of commercial agriculture, this rate of varietal replacement is common. However, there are still areas of small-farm agriculture, such as northeastern India, where the rate of varietal replacement is too low to assure farmers stable yields as well as enable them to benefit from genetic gains in

[13] In addition, the introduction of MVs led to investment in irrigation facilities and continuous cropping of rice throughout the year, and indirectly aggravated the buildup of pest populations.

[14] The only exception to this is the use of herbicides in some wheat growing environments. It is likely that the shorter stature of semidwarf wheats along with their more intensive cultivation, has promoted the growth of some grassy weeds. However, rising labor costs in many areas have been the major driving force in increased adoption of herbicides (a similar situation holds for rice; see Naylor, 1994).

yields incorporated into new varieties (Figure 7, Heisey 1990). These areas have yet to experience the Type B varietal change characteristic of post-Green Revolution areas, in which productivity growth and sustainability depend on varietal replacement at least once a decade.[15]

Given the resources devoted to maintenance breeding and the considerable costs of developing appropriate institutional mechanisms to promote rapid varietal replacement at the farm level, research programs now place greater emphasis on developing more durable forms of pest resistance (Lipton with Longhurst 1989, Alexander and Bramel-Cox 1991). However, the development of durable resistance may have a cost if farmers replace varieties less frequently, thereby failing to realize genetic gains in yield potential in new varieties.

Breeding for resistance to most insect pests and diseases represents a cost-effective way of increasing both productivity and sustainability (Hoffman, Thurston, and Smith 1993). New techniques in biotechnology also emphasize improved resistance to a wider range of pests and should expand the potential to improve pest resistance (see below).

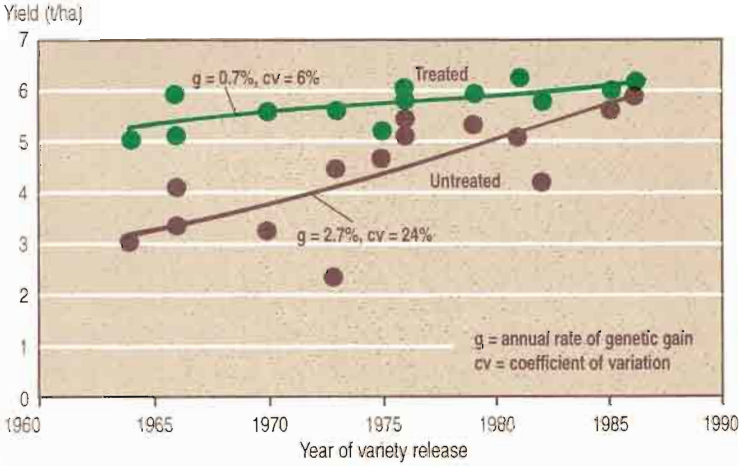


Figure 6a. Yields of commercial wheat varieties with and without fungicide, Obregón, Mexico, 1990-92.

Note: The gains in yield for treated plots include only the effects of increased yield potential, while gains for untreated plots also include the effects of maintenance of disease resistance, since all varieties were resistant at the time of release.

Source: K. Sayre (pers. comm.). Data for normal planting in 1990-91 and 1991-92.

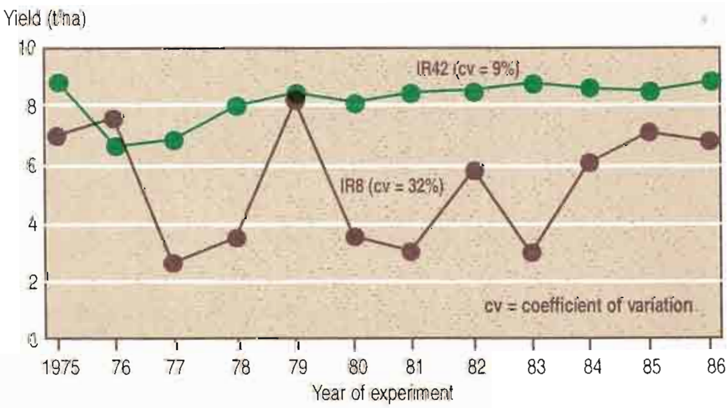


Figure 6b. Yields of rice varieties of different vintages, 1975-86.

Note: IR8 was released in 1966, IR42 in 1977
Source: Khush (1990)

MVs and On-farm Diversity

Promotion of broad genetic diversity in farmers' fields provides insurance against losses from unexpected causes, such as a new disease, and complements efforts to improve and maintain resistance to specific known pests through the manipulation of specific genes. Biological diversity in farmers' fields at the crop level is enhanced by spatial and temporal diversity. Spatial diversity is promoted by releasing varieties with different and broad genetic backgrounds and by crop mixtures; temporal diversity occurs when varieties are replaced over time with newer varieties derived from different gene pools.[16]

15 Assuming that there is a three-year lag from the time a variety is released until its initial adoption, the weighted average age of varieties in farmers' fields would have to be less than 13 years to satisfy the minimum definition of Type B varietal change once a decade.

16 Of course, diversity *within the cropping system* in terms of cropping patterns and rotations may be more important than diversity *within an individual crop* in promoting on-farm diversity.

Figure 7. Weighted average age of wheat varieties grown by farmers, 1980s.
Source: Brennan and Byerlee (1991), Byerlee and Moya (1993).

A claim common to the anti-Green Revolution "folklore" is that on-farm diversity was sharply reduced by the adoption of one or very few MVs, which replaced many genetically diverse local varieties (Wilkes 1992, Brush 1992, Berg et al. 1991, Hobbelink 1991, Cleveland and Soleri 1989, Kloppenburg 1988). In fact, the situation was far more complex. In many cases and especially in irrigated areas, genetic diversity in farmers' fields in the pre-Green Revolution period was already limited. For example, farmers in northern India and the irrigated areas of Pakistan already used improved varieties of wheat extensively, and the concentration on one or two closely related varieties was very high prior to the release of MVs in the 1960s.[17] The Green Revolution actually caused one or two dominant varieties to be replaced by a similar number of MVs. The more recent spread of MVs into rainfed areas has probably led to more genetic erosion, since these are the areas where landraces were widely grown. However, the replacement of local landraces by MVs does not necessarily imply greater genetic vulnerability to all diseases, since the disease susceptibility of landraces was often very high and recent molecular analysis has shown that genetic diversity among landraces is often surprisingly narrow (M. Sorrells, pers. comm.).

Nonetheless, there was reason to be concerned about the dominance of a few MVs in the Green Revolution period. In the post-Green Revolution period, with the release of many and more genetically diverse varieties, genetic diversity on the farm has generally widened. For example, in the Punjab of Pakistan, the genetic diversity of varieties planted by farmers increased significantly in the 1980s (Souza et al. 1994).[18] However, in our enthusiasm for biodiversity, the benefits of diversity have been accepted uncritically and the possible costs of alternative strategies of increasing diversity ignored. To be sure, diversity can be increased if farmers grow a wider number of genetically diverse varieties. However, this may entail a considerable yield tradeoff, since farmers have become quite adept at selecting the highest yielding varieties.[19] Other approaches have also been tried with limited success, since they entail sacrifice in genetic gains (e.g., the case of multilines of wheat in India)[20] or require frequent seed replacement (e.g., varietal mixtures) (Browning 1988). In short, increased diversity at the farm level is desirable as an insurance for increasing stability, but the costs of alternative strategies for achieving this stability need to be weighed against the potential benefits.

Plant Breeding and Natural Resource Management

Finally, MVs can promote sustainability through incorporating tolerance to abiotic stresses, especially poor soil fertility, soil toxicities, and drought stress, which may potentially lead to greater input efficiency. The most tempting of these approaches is the development of varieties that are more efficient at using major soil

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17 Prior to the Green Revolution, the adoption of improved wheat varieties had reached about 75% of the area over much of the irrigated wheat area of South Asia. Of this area, one variety usually accounted for more than half of the total wheat area, and the remaining area under improved varieties was sown to one or two closely related varieties (Sukhatme 1945, Ministry of Agriculture and Works 1966, Seghal 1969). A similar situation prevailed in much of North Africa, where Florence Aurore, a variety developed in the 1930s, dominated large areas in medium and higher rainfall regions.

18 However, in rice, the dominance of one variety continued well into the post-Green Revolution period. The variety IR36, released in 1976, became the most popular variety ever, planted on more than 20 million hectares in the early 1980s (Anderson and Herdt 1989).

19 In India, there is a significant correlation between the yield of a variety and its commercial success (Jain and Byerlee 1994). Thus increasing diversity through wider adoption of more varieties is difficult because of the yield sacrifice involved.

20 A considerable effort was made in India to produce multilines of wheat—that is, mixtures of genetically similar genotypes, with each genotype incorporating different sources of rust resistance. The desired product was developed, but farmers did not adopt multilines, because over the years required to develop the multilines, newer, higher yielding varieties had become available (Jain and Byerlee 1994).

nutrients, such as nitrogen and phosphorus (Bramel-Cox et al. 1991, Francis 1990, Dambroth and El Bassam 1990).[21] Although the higher responsiveness of MVs to fertilizer use contributes directly to increased input efficiency, there appears to be scope for further progress in this area, but the costs of alternative strategies have not been assessed adequately. For example, is it cost effective to breed for improved nitrogen use efficiency, versus investing in research on crop and resource management to improve nutrient supply and enhance efficiency? Since the cost of plant breeding increases at least proportionally (or the rate of progress with the same level of resources decreases) with the number of traits emphasized (Francis 1991, Arnold and Innes 1984), there is likely to be a tradeoff between productivity growth and sustainability. And improved nutrient efficiency may not be sustainable if it is achieved through increased nutrient uptake, since this implies soil nutrient mining over the long run (Lipton with Longhurst 1989).[22] On the other hand, in small-farm agriculture, MVs that allow improved input efficiency in a sustainable manner have the advantage that the cost of transferring seed of a new variety is likely to be much lower than the cost of transferring the improved information and skills that typically characterize crop and resource management approaches to enhanced input efficiency (Byerlee 1987).

There are other ways in which MVs may interact with sustaining the resource base. For example, it may be possible to develop varieties with root systems that reduce leaching of nitrates (Fischer 1993). Reduced tillage, which is increasingly promoted for soil conservation, may lead to a change in pest populations (since crop residues are not removed or burned); adoption of this practice might be facilitated by developing varieties that incorporate resistance to these new pests. However, some of these practices may trade off input use of one type for another. For example, the development of MVs for direct seeding of rice, a practice spreading rapidly in Asia, may promote greater use of herbicides (Naylor 1994).

In summary, breeding for abiotic stresses promises to contribute to the sustainability of agricultural systems. However, in general, progress in breeding for biotic stresses will be faster (Table 8).

Table 8. Prospects for developing specific traits compatible with sustainable systems, through plant breeding

Trait	Probability of success
Insect resistance	High for most species
Pathogen resistance	High for most species
Nematode resistance	Moderate to low
Competition tolerance (e.g., weeds)	Variable
Drought tolerance	Moderate
Problem soil tolerance	Moderate
Nitrogen-use efficiency	Moderate
Phosphorus-use efficiency	Moderate
Root system modification	Moderate

Source: Francis (1993).

21 Sustainability may also be enhanced through tolerance to deficiencies in microelements or tolerance to toxicities induced by excess of some elements (Fischer 1993; Dambroth and El Bassam 1990).

22 Modern varieties may also increase nutrient efficiency through improved nutrient partitioning to grain within the plant.

Maintaining the Momentum: Future Challenges

In looking to the future, the two new opportunities for maintaining the momentum in productivity gains and sustainability through MVs appear to be: 1) the exploitation of heterosis through development of hybrid varieties and 2) the use of the new biotechnologies.

Exploiting Heterosis

The use of hybrid seed to exploit yield gains from heterosis in inbred populations is, of course, not new. It has been the basis of much of the productivity growth in industrialized countries, especially in maize. However, hybrid seed has not been used widely in developing countries, even in a crop such as maize where its yield advantage is highest. The early programs in technical assistance to developing countries in the 1940s and 1950s did emphasize hybrid maize, especially in Latin America, India, and Kenya. Although these programs had some notable success, both in introducing hybrid seed in commercial agriculture (e.g., Brazil) and, later, in small-farm agriculture (e.g., Kenya), the emphasis switched in the 1960s toward open-pollinated varieties for a number of reasons. First, improved breeding methods were developed for open-pollinated populations. Second, many countries failed to develop the seed industries needed for farmers to replenish hybrid seed annually. Third, it was commonly believed that hybrid seed was inappropriate for small farmers' circumstances, not just because of the cost of replacing seed annually but also because the yield advantage of hybrid seed was thought to express itself only under high-input conditions (e.g., Lipton with Longhurst 1989). CIMMYT and its predecessor organization, the Office of Special Studies, undoubtedly influenced this trend away from hybrid maize, since CIMMYT focused exclusively on open-pollinated varieties (OPVs) when it closed its hybrid program in the 1960s.

This situation began to change in the 1980s. It is now recognized that an effective seed industry is also needed for OPVs, although producing seed of OPVs provides little incentive for active private sector participation. Evidence has also accumulated that hybrid seed may be highly successful under small-farm conditions (e.g., the success stories of El Salvador, Kenya, Zimbabwe, and some areas of India), often with use of very low levels of external inputs and in very marginal environments, such as in Southern Africa (Smale and Heisey 1994).[23] Parallel evidence for hybrid sorghum and millet in India (Pray, Mueller, and Ribeiro 1991) reinforces the reconsideration of hybrid seed as an appropriate strategy except in the most marginal areas. Many NARSs have now initiated or strengthened programs in hybrid maize, and CIMMYT presently devotes considerable resources to providing suitable products, such as inbreds, to these programs, as well as to the private seed companies that have recently emerged in many countries (see "The Privatization of Research," page 19). It is likely that these initiatives, along with widespread liberalization and privatization of the seed industry, will lead to much greater adoption of hybrid maize in the next decade.

Recent developments in hybrid rice have the potential for even more far-reaching changes. Hybrid rice was pioneered by China, where it first began to be adopted in the late 1970s. Currently half of China's rice area is sown to hybrids. India has also initiated commercial hybrid seed production, and IRRI has a strong program in hybrid rice. Thus hybrid rice, like maize, may lead to significant increases in productivity in the next decade. However, unlike maize seed, hybrid rice seed is relatively costly and the yield advantage of hybrids over conventional MVs is modest (about 15%), so adoption will likely occur in high-potential and more commercially oriented rice-growing areas (Seghal 1992, Lin 1994).

The remaining important cereal crop for which hybrid seed is not commercially significant is wheat. Although several companies have invested substantial resources in hybrid wheat, the results have not been encouraging (Knudson 1986, Virmani and Edwards 1983). Some hybrid wheat seed is sold in Argentina, Australia, the US, and Europe. However, without a breakthrough to reduce the cost of hybrid seed (a possibility with new biotechnologies — see Mariani et al. 1990), it is unlikely that hybrid wheat will contribute significantly to productivity growth in the next decade.

The Potential of Biotechnology

A great deal has been written on both the potential benefits as well as the dangers of the new biotechnologies. Biotechnology will not result in a new Green Revolution for cereal crops, nor will the results be noticeable in farmers' fields until well into the next decade. The new technologies promise two major advances in conventional plant breeding (McCouch, Ronald, and Kyle 1993). First, they offer the potential to reduce the cost of varietal development 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). To date there has been little effort to obtain a precise estimate of the potential cost advantage of using the new techniques. However, a recent study found that the average cost of an improved wheat variety in developing countries is about US$ 1 million, and more than double that if only successful wheat varieties are included (Bohn and Byerlee 1993). Brennan (1989) has shown that in Australia using techniques such as tissue culture to "speed the breeding" has substantial potential payoffs, since a major factor affecting the profitability of plant breeding programs is the long lag between when research costs are incurred and when benefits are received by farmers.

[23] In Malawi, even with no fertilizer applied and in a severe drought year, hybrids outyielded local varieties in farmers' fields by over 50% in more than 100 demonstrations (Smale and Heisey 1994). Duvick (1992) has also documented superior performance of hybrids under stress conditions.

The new biotechnologies are better known (and feared) for their potential to transfer genes from unrelated species, which would not be available through conventional breeding. For the next decade or so, only traits that are expressed through single or a very few genes are likely to be successfully inserted into cereal crops. Thus genetic transformation of cereal crops will emphasize pest resistance (especially against insects and viruses), herbicide resistance, quality traits, and possibly genetically induced male sterility to facilitate hybrid seed production. Of these possibilities, the transformation of rice for resistance to several pests through the rice biotechnology network is the most advanced in terms of potential application in developing countries. This program, which will have invested over US$ 100 million up to 1995, has inserted eight new genes for pest resistance into rice (R. Herdt, pers. comm.). It is likely that varieties carrying some of these genes will be released by the end of this decade in Asia.

In maize, too, there are several efforts both in the private and public sectors to transform tropical and subtropical maize for insect resistance. While these efforts are much more modest for maize than for rice, it is likely that commercial varieties with improved resistance to one or more insects will be available by the end of the decade. An additional, and more controversial, prospect is the availability of maize varieties genetically engineered for herbicide tolerance. While many consider this option inappropriate for small farmers and have rallied against biotechnology research on these grounds (e.g., Hobbelink 1991, Neubert and Knirsch 1992), in some situations herbicide-tolerant maize *may* be environmentally and small-farmer friendly. For example, in maize-based hillside farming systems of Mexico and Central America, small farmers have switched from traditional slash and burn methods to conservation tillage, but they use toxic herbicides. Genetically engineered maize varieties with tolerance to less toxic but equally effective herbicides merit further analysis, since such varieties may benefit farmers' health and reduce environmental degradation (by facilitating adoption of conservation tillage).

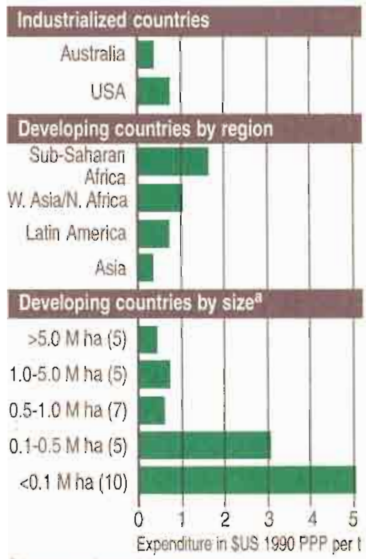
In summary, the new biotechnologies will not have much impact on cereal production in developing countries until the next decade. Nor do they offer much scope to increase yield potential; rather their primary impact will be in enhancing genetic diversity, stabilizing yields, and reducing pesticide use — all characteristics compatible with a more sustainable agriculture. For developing countries, the main issues in employing these techniques are research and development costs (especially in small countries), risks (e.g., breakdown of resistance, biosafety), and access to the new technologies developed in the private sector of industrialized countries (see discussion, page 19).

[24] A recent survey of wheat research programs found that about 75% of their resources were devoted to varietal development (Bohn and Byerlee 1993).

Emerging Economic and Institutional Issues in Plant Breeding

The Development of Public Sector Programs

Beginning in the early 1960s and with a strong impulse from the Green Revolution successes, investment in agricultural research in developing countries increased by an average of over 6% annually to the 1980s (Anderson, Pardey, and Roseboom 1994). Much of this increased investment was reflected in the organization of interdisciplinary commodity research programs coordinated at the national level. Although conceived as a way of promoting integrated research on all aspects of crop improvement and management (Moseman 1977), these commodity research programs were in practice heavily dominated by plant breeding, with most resources oriented to varietal improvement.[24]



[a] Number of countries in parentheses.

Figure 8. Expenditure on wheat breeding research per ton of wheat produced, 1992. Source: Bohn and Byerlee (1993).

For major commodities, such as the cereals, the level of research investment is now quite high compared to levels in industrialized countries. For example, more than 1,000 scientists are estimated to work in wheat improvement in developing countries, with a total expenditure of over US$ 100 million in 1990 (Bohn and Byerlee 1993). Both the number of scientists and expenditure level per unit of wheat output is at least as high in developing countries as in industrialized countries (Figure 8). More striking is the fact that for many smaller countries or programs within countries, the level of investment is several times higher relative to the US or Australia (Figure 8).

These crop improvement programs have been highly productive if productivity is measured by the number of varietal releases (Figure 4) and by the returns on the investment (Byerlee and Traxler 1994). However, given that genetic gains in yield and other traits have contributed a maximum of 2% annually to growth in productivity, it is likely that returns to research investment have been declining. In other words, investments in research, whether measured in dollars or numbers of breeders, have increased faster than the gains in productivity of varieties released. This situation is not unique to developing countries but characterizes plant breeding efforts in major crops in developed countries as well (Duvick 1991, Byerlee and López-Pereira 1994).

One justification of the heavy investment in crop improvement programs in developing countries has been the belief that biological technology does not travel well across national and subnational boundaries, and hence imported germplasm requires adaptation by local plant breeding programs (Jarrett 1982, Hayami and Ruttan 1985, Englander 1991, Evenson 1994). In fact, it seems that for some crops there is substantial opportunity to evaluate and directly release imported materials. A case in point is germplasm from the international system, which is bred to be widely adapted and is often released directly by NARSs (Figure 9a). This international system is based on crosses and selections by IARCs combined with an extensive testing program conducted in collaboration with dozens of NARSs. For example, half of the 1,000+ wheat varieties released in developing countries over the past two decades have been based on crosses and selections made by the CIMMYT Wheat Program in Mexico, which were tested extensively in CIMMYT/NARS collaborative nurseries. The proportion of direct releases from this IARC/NARS network is lower for rice and maize but is still substantial, and, significantly, it has continued to increase steadily for two of the three

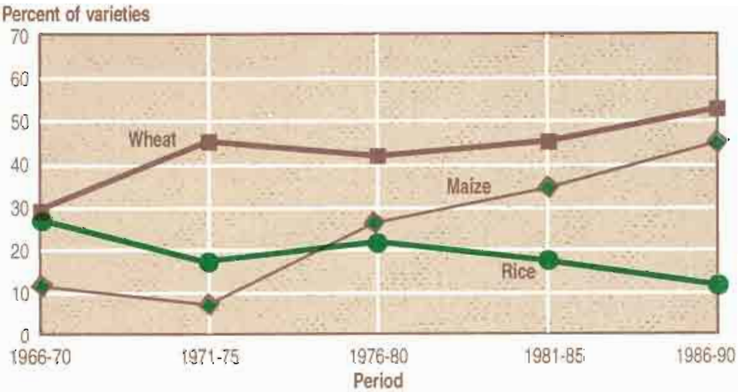


Figure 9a. Percent of all varieties in developing countries based on IARC crosses, 1966-90.

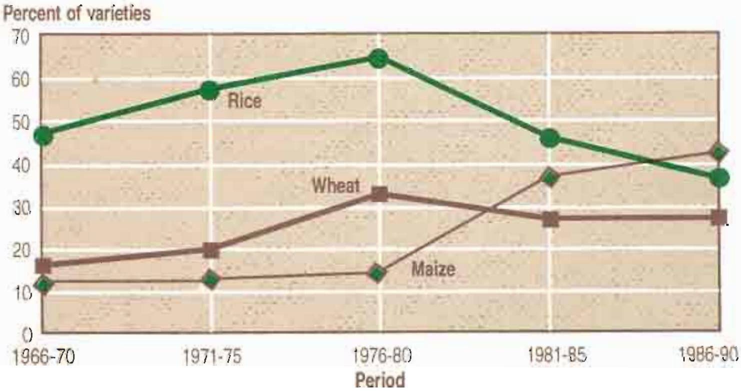


Figure 9b. Percent of varieties in developing countries based on NARS crosses with IARC parent, 1966-90.

Note: All varieties in developing countries outside of China. For maize, IARC crosses are varieties with mostly IARC germplasm, and NARS crosses are varieties with some IARC germplasm.
Source: Byerlee and Moya (1993); López-Pereira and Morris (1994); and R. Evenson (pers. comm.).

crops in the post-Green Revolution period (rice is the exception). The corresponding proportion of *area sown* to IARC-based germplasm is also high. For example, about half of all area under improved wheat varieties in developing countries is sown to germplasm from this international system. In the case of rice in Indonesia, despite the presence of a strong local rice breeding program, over half of Indonesia's rice area in the 1980s was sown to direct releases from IRRI-based materials (Pardey et al. 1992). Spillovers of varieties from one country to the other are also common, accounting for about 10% of the rice and wheat varieties released in developing countries. Finally, materials from the international system have been widely used as parents in adaptive breeding programs (Figure 9b).

Maredia, Byerlee, and Eicher (1994) have substantiated the extent of these potential spillovers through an analysis of international yield trial data for wheat. Their conclusions support earlier work by Englander (1991) that showed a significant yield advantage among varieties bred by a country for a specific environment, compared to varieties bred for a different environment in that country or in other countries. But unlike Englander, Maredia et al. concluded that, for the two major wheat "mega-environments" (irrigated and high rainfall spring wheat areas), materials from the CIMMYT/NARS network had a highly significant yield advantage over locally bred materials. Even in the more marginal environments, there was no disadvantage of these materials.[25] Of course, desirable traits other than high yields, such as specific quality traits valued in a particular area, may be developed more efficiently through local breeding programs. This is particularly true for crops such as rice and maize, for which locally desired quality traits may be quite specific to a country or region within a country (Unnehver 1986, Smale et al. 1991).[26]

Although economic analyses of research on major crops continue to show high returns, some caution should be used in extrapolating these results to the future. Most studies of rates of return have focused on large producers of a commodity and have included periods of rapid growth in productivity, especially the Green Revolution period. Maredia, Byerlee, and Eicher (1994) have shown that, given likely spillovers from IARCs and NARSs, a crop improvement program requires a substantial production target to justify the investment in a local crossing program. They conclude that many wheat programs in developing countries operate at uneconomic levels, and efficiency in these cases could be increased through a smaller program to evaluate imported materials, or materials from other programs in the same country, rather than a full crossing program to develop new varieties. Resources freed through consolidation of plant breeding programs could be used in other areas with potentially high payoffs (e.g., biotechnology or crop and resource management).

These recent studies seriously question the conventional wisdom that 1) biological technology, at least crop varieties, is very site-specific and 2) developing countries underinvest in research, at least for crop improvement research. Given the apparent economies of size in crop improvement research (Bohn and Byerlee 1993) and the similarity of some environments across countries and continents (Winkelmann 1994), there is a strong case for consolidating crop improvement programs in NARSs and strengthening regional and international research institutions to improve the efficiency of overall resource use, especially among small NARSs. This may imply also that NARSs shift some resources from crop improvement research toward more site-specific research activities, especially research on crop and resource management.

These issues were not so important in a climate of relative resource abundance for crop improvement research. However, they are likely to come to the fore in the near future, given that resources available for agricultural research have fallen sharply in many NARSs (e.g., Karanja 1993, Traxler and Byerlee 1992, Macagno and Gómez-Chao 1992). At the same time, resources available to

[25] These results are contrary to those of Englander (1991), who also analyzed international yield trial data but found that locally developed materials outperformed CIMMYT materials. However, Englander employed the country of variety release as the measure of the origin of the variety. In fact, many of these "locally developed varieties" originated in CIMMYT. Part of the confusion arises because CIMMYT does not release varieties; it distributes breeding material to research programs around the world.

[26] However, with increasing commercialization of food consumption, tastes tend to become more homogeneous over time, thus increasing the potential to utilize spillins.

the IARCs, especially for crop improvement research, have been eroded (for example, CIMMYT's budget declined by more than one-third in real terms over 1988-94). This new situation requires the evolution of new institutional mechanisms to exploit the complementarity of international, regional, and national research efforts.

The Privatization of Research

One approach to promote greater efficiency in crop research and attract additional resources is to increase the involvement of the private sector in crop research (McMullen 1987, Pray and Echeverria 1991). The most obvious opportunity for the private sector is to conduct research on crops for which profits can be appropriated through trade secrets in the form of hybrid seed. In the USA, which pioneered hybrid maize, the private sector now accounts for about 90% of the research expenditures on maize breeding (Huffman and Evenson 1993). In developing countries there are also many examples of significant involvement of the private sector in the hybrid seed market, but outside of a few commercial maize producing areas, especially in Latin America, private sector investment in research has generally lagged. The public sector still provides the bulk of the research effort, even in areas where the private sector is active in producing and marketing hybrid seed.

In part, the relatively limited participation of the private sector in research on varietal improvement reflects the limited size of the potential market in many countries. It also reflects institutional and economic policies and attitudes, which until recently often provided disincentives for private sector investment in research, especially by the large multinational seed companies that had the resources and know-how to provide the leadership. In addition, successful cases of widespread adoption of hybrid seed by small farmers have been based on a combination of public sector research and extension, and private sector seed production and marketing. By underwriting research and extension costs, the public sector has helped to reduce the cost of hybrid seed to small farmers to a fraction of what is charged in commercial maize producing areas (Byerlee and López-Pereira 1994). Large seed companies that have a higher overhead in research expenditures and promotion costs have not demonstrated a comparative advantage in developing a market for hybrid seed in small-farm agriculture.

Table 9. Investment in maize breeding in the public and private sector, 1990

	Africa	Asia	Latin America	USA
Number of maize breeders				
Public sector	86	175	283	72
Private sector	38	169	164	641
Total number of maize breeders per million tons of maize produced	7	15	8	4

Source: Byerlee and López-Pereira (1993).

Nonetheless, recent policy changes and greater emphasis on privatization in all sectors of the economy have produced an upsurge in private sector interest in agricultural research. In Latin America and Asia, investment by the private sector in maize breeding is now substantial (Table 9), and multinational seed companies invest considerably more in maize research in the developing world than do IARCs. Similarly, there is increasing investment by several private companies in hybrid rice research in Asia.

In addition to trade secrets, the other approach widely used to promote private sector investment in research, especially in non-hybrid crops such as wheat, is to employ legal protection through some form of intellectual property rights (IPRs), such as plant varietal rights and, more recently, patents. Although these approaches are used in commercial agricultural areas of developing countries — in fact, the bulk of the wheat area of Argentina is sown to varieties developed by private seed companies — they are unlikely to be effective in small-farm agriculture. The cost of enforcing IPRs for a multitude of small farmers is prohibitive relative to the royalties that private companies may gain. However, much research on biotechnology is conducted in the private sector of industrialized countries and protected by IPRs, so a major question for developing countries is whether they should implement IPRs to enable their public research systems to obtain access to these technologies. The question is highly charged emotionally, and there is no easy answer for developing countries, given that industrialized countries have unilaterally institutionalized patenting for biological organisms and processes.

A patent on a variety or gene in industrialized countries does not mean that small farmers in developing countries are denied access to that variety or gene, even in the absence of IPRs in developing countries. Once a variety with a novel and useful characteristic, such as resistance to a particular pest, is released in any country, it is only a matter of time before it becomes available to breeders in other countries, who can transfer the trait to other materials through conventional breeding methods. This is true whether or not a country adopts IPRs for plants.[27]

Does this imply, as some have argued, that developing countries can ignore the pressure to implement IPRs for plants and biological processes? There are several reasons why this may not be the best strategy (Platais and Collinson 1992). First, although novel germplasm will be relatively easy to obtain after it is first released to farmers in one country, there will still be a delay of several years in obtaining and adapting the germplasm to local needs. If IPRs are in place, a transfer agreement could probably be negotiated at a much earlier stage, enabling the benefits of the technology to become available to small farmers much sooner, before the technology becomes obsolete. Second, and as important as new germplasm products, is the use of new biotechnological processes to create new varieties more efficiently. Examples of these processes include the use of molecular markers to track genes or methods to conduct genetic transformations for traits that are more appropriate to local needs. These technologies are much less likely to be available on the "black market" and will have to be purchased under some type of licensing or royalty system. Third, many larger developing countries with strong biotechnology research programs will be in a position to sell, exchange, or export products based on the new technologies, and this will be facilitated by legal protection for their products. Finally, IPRs for biological processes and products are now an integral part of international agreements, such as the GATT. If a country wishes to benefit from these agreements as part of its overall economic policy, IPRs on plants may be needed.

The increasing concentration of research on biological technologies in the private sector, often in multinational companies in developed countries, means that new institutional arrangements will be required to facilitate the flow of these technologies to developing countries. If the new technologies can be incorporated into hybrids, then the private sector itself will likely be the main vehicle for transferring the technology, either through direct investment by the multinationals themselves or through some type of licensing agreement with local companies. However, for non-hybrid crops, the cost of enforcement will in most cases require that the public sector research program or an international institution negotiate an agreement to use and distribute the technology. Until hybrids of the two main cereal crops, rice and wheat, are used extensively, the public sector will retain its central role in providing improved technology to small farmers.

The key issue that developing countries will have to resolve is the cost of *not* having IPRs, in terms of delayed access to new technologies and the potential to develop and export their own biotechnological innovations. These costs must be balanced against the cost of royalty payments and licenses for acquiring the new technologies (Perrin 1994, Seghal 1992).

In summary, although private sector research is increasing in developing countries, it will not replace public sector efforts in the foreseeable future, especially in small-farm agriculture. Rather I see opportunities for a complementary relationship that will enhance the effectiveness of both sectors. In commercial agricultural areas, especially in Latin America, the private sector is already quite active, and there are opportunities for the public sector to reallocate research resources toward basic and strategic research and toward production areas that the private sector has bypassed — especially marginal areas. The growing trend toward providing

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27 The recently negotiated GATT agreement provides a mechanism to police unauthorized use of protected intellectual property. However, the effect in practice is still unclear, especially if industrialized countries are seen as denying poor farmers access to new technologies.

profit incentives for public sector research through royalty payments on the use of public sector varieties and hybrids is worrying. A "profit-oriented" public sector is more likely to compete with the private sector in applied research for high-potential and commercial agricultural areas than to complement private sector efforts.[28]

Conclusions

This review has confirmed that the spread of MVs for the major cereal crops, with the possible exception of maize, expanded steadily in the past decade and has reached high levels in most developing regions. Moreover, in areas already sown to MVs, the continuous release of newer generations of MVs with higher and more stable yields has contributed significantly to growth in productivity. In post-Green Revolution agriculture, MVs have the potential to increase productivity by a steady 0.5-2.0% annually and represent half or more of the overall increase in Total Factor Productivity. These conclusions lend support to a recent claim that " better adapted crop varieties are the cheapest, most reliable and environmentally safest way to increase productivity and secure the world's food supply" (Bosemark 1993).

One of the key issues in research policy for plant breeding programs is the relative emphasis to give to extending the frontier of MVs to new areas (Type A changes) versus exploiting the potential for productivity gains through varietal change in areas that have already benefitted from MVs (Type B changes). In rice and wheat, much of the remaining area not sown to MVs is very marginal (e.g., upland rice areas or very dry wheat areas), and hence the potential for MVs to have much impact is very limited. This is particularly so since breeders have to give considerable weight to other varietal traits, such as quality and crop by-products, in order to produce successful MVs for these areas. However, in the case of maize, there are still substantial opportunities for the area under MVs to expand. Type A changes in productivity will be important for maize over the next decade, especially in small-farm agriculture.

The process of intensification of input use, stimulated by the adoption of MVs, has continued long after the adoption of MVs was completed, and only recently has input use leveled off in the most advanced areas. Although MVs have been widely criticized for encouraging the use of external inputs to the detriment of the environment, these critics have not taken account of the fact that MVs do allow for external inputs to be used more efficiently and provide an opportunity to reduce the use of environmentally harmful external inputs, especially pesticides. Thus the process of input intensification, aided by the adoption of MVs, must continue, especially in areas where input use is still very low, such as northeastern India and much of Africa. However, in the most advanced areas, use of high levels of chemical fertilizers may have important environmental costs that need to be addressed.

Modern varieties have undoubtedly made important contributions toward a sustainable agriculture, both indirectly, through the adoption of land-saving technologies, and directly through the more efficient use of external inputs and the increased stability of production in many post-Green Revolution areas. In the future, the further diffusion of MVs as well as the development of newer generations of MVs will continue to be important in promoting a more sustainable agriculture. One of the most important contributions of MVs is enhanced pest resistance, permitting reductions in the use of harmful pesticides and promoting greater stability of yields. There are additional opportunities for MVs to promote greater nutrient efficiency, as well as to complement the adoption of sustainable practices, such as conservation tillage. Most observers also call for greater efforts by plant breeders to increase on-farm diversity. However, caution is needed in asking plant breeders to incorporate more objectives into varietal development, since there are likely to be significant tradeoffs between direct contributions of MVs to sustainability and indirect contributions through increases in productivity. In addition, plant breeding may be a blunt instrument for achieving some goals, such as improved nitrogen efficiency, compared to investment in crop and resource management or even other

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28 In addition, the possible negative externalities of private sector breeding efforts that do not take sufficient account of the social benefits of pest resistance need to be considered (Ballantyne, Murray, and Brennan 1994, Coffman and Smith 1991).

measures, such as the elimination of fertilizer subsidies.

There is every reason to expect that the contributions of MVs to productivity and sustainability will be maintained in the future, largely through continual varietal replacement (Type B changes). In the future, the development of hybrid varieties and tools such as the new biotechnologies will enable faster progress in some regions and crops as well as in addressing some problems. However, neither hybrids nor new research tools will lead to a departure from the steady progress in genetic gains achieved over the past two decades through conventional breeding. Significantly, the new biotechnologies show their greatest promise for initial commercial application through enhanced pest resistance and yield stability, and thus will make important contributions toward a more sustainable agriculture.

Aside from highlighting past and potential contributions of MVs to sustainable agriculture, this paper has also highlighted emerging challenges in the economic and institutional environment in which plant breeding is conducted at the national and international levels. The results of recent research lead us to question two assertions that form part of the conventional wisdom about agricultural research. First, there is growing evidence that biological technology is internationally transferable and that there are significant economies of size in plant breeding. The number of varieties based on IARC crosses that have been released in developing countries has continued to rise in the post-Green Revolution period, providing evidence of the broad adaptability of the genetic products and the continuing contribution of the IARCs. Second, there is growing evidence that many NARSs, especially smaller NARSs and small regions within large countries, have overinvested in programs to develop technologies (i.e., produce varieties), rather than evaluate materials developed by other NARSs and IARCs. These findings, together with the growing scarcity of resources for agricultural research in both NARSs and IARCs, and the additional demands on agricultural researchers to address environmental issues, suggest a need to consolidate plant breeding programs and carefully analyze the comparative advantage of IARCs and NARSs of different sizes in different types of research.

Finally, the private sector is playing a greater role in research aimed at the development of MVs. However, outside of the commercial agricultural areas of developing countries, the public sector will continue to provide the leading role in plant breeding research and activities that support such research, including biotechnology. This is true even for crops like maize and increasingly rice, for which the use of hybrid seed and bioengineered germplasm will expand rapidly over the next few years. Nonetheless, there are opportunities for greater complementarities between private and public sector research that can contribute to more efficient use of research resources in the future.

Modern varieties have been a driving force in productivity gains in developing world agriculture over the past 25 years, and there appears to be no reason why MVs should not continue to be an important source of productivity growth over the next 25 years. As the international community and developing countries shift emphasis toward environmental concerns and sustainability, MVs can play an important role — both through offering "more of the same" and through carefully selected efforts to breed varieties with specific varietal traits that facilitate the adoption of more sustainable agricultural practices. However, to meet these future challenges, significant changes will be needed in the organization and funding of agricultural research aimed at varietal development.

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