# Technical Change, Productivity, and Sustainability in Irrigated Wheat Systems of Asia: Emerging Issues

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## Introduction

Wheat is the second major food grain in Asia, after rice. The Asian wheat crop covers 62 million ha, which is 23% of the total area sown to cereal crops in the region.[1] Most wheat in Asia--about 75%--is grown under irrigation or in areas receiving adequate rainfed moisture. In the irrigated cropping systems of the Indo-Gangetic plain, extending from Pakistan through to western Uttar Pradesh in India, and in much of northern China as well, wheat is the principal food crop. In other locations, including Bangladesh, China (from the Yangtze Valley south), and northeastern India, wheat is often grown in the short cool season after rice, the chief staple food.

Over the past 25 years, wheat production in South and East Asia rose by nearly 6% annually, which is an extraordinary rate compared to earlier rates of growth in wheat production in Asia or nearly anywhere else in the world. Furthermore, growth in wheat production throughout Asia is high compared to growth in the production of other cereal crops. For example, production of rice--the crop that, along with wheat, was the catalyst for the Green Revolution in Asian agriculture--grew at just about 3% annually during the same period.

Such high growth rates in production are unlikely to persist in the future. Fortunately the pressure for such rapid increases in cereal crop production will also diminish in years to come as population growth slows and the income elasticity for staple foods declines, reducing the rate at which demand for cereals rises. But for several reasons it will be essential to achieve production gains of about 3% per year. First, the area sown to cereal crops will probably diminish, and hence yield gains must compensate for any decline in area; second, the productivity of some wheat systems may actually be declining; and third, improving the productivity of cereal crops is the best opportunity to improve the incomes of the multitude of poor people in Asia, who depend more than others on the production and consumption of cereal grains.

This paper outlines recent trends in Asia's irrigated wheat cropping systems, giving particular attention to South Asia. It focuses on emerging problems, both technical

1 Excluding West Asia.

and institutional, that will impinge strongly on farmers' ability to maintain gains in agricultural productivity and sustain their resource base over the next 10-20 years. The paper concludes that a new strategy must be adopted to increase or even sustain productivity in Asian cropping systems in the future. This strategy not only implies profound changes in agricultural research priorities, but also in the institutions that foster technical change in agriculture.

## Overview of Recent Trends in Wheat Production in Asia

Production of all cereal crops grew at an unprecedented rate in Asia from the 1950s to the 1960s. This trend was reversed in the 1970s, and by the 1980s the growth rate of cereal production was only slightly higher than it was in the 1950s (Figure 1). This reversal reflects a radical decline in the growth of area sown to cereals as well as a more gradual slowing in the rate of growth in yields. As a result, over the past four decades the relative contribution of increased area and yield growth to cereal production has changed completely. In the 1950s increases in area sown to cereal crops accounted for about half of the growth in cereal production in Asia. This proportion has declined in every decade since then, so that area sown to cereals stagnated in the 1980s; only Southeast Asia shows significant potential for increasing the area sown to cereal crops.

Trends in wheat production generally mirror trends in production of all cereals. Wheat area increased slowly in the 1980s as farmers in some areas continued to substitute wheat for other crops, especially coarse grains. Moreover, in most of the wheat-producing nations of Asia--Pakistan, Bangladesh, and China (since 1984)--growth in wheat yields fell in the 1980s relative to the growth rate seen in the 1970s (Figure 2). The major exception to this trend is India, where increased growth in yields in areas such as Uttar Pradesh compensated for the declining growth rate in yields in other areas.

These trends have two important implications in projecting future food production in Asia. First, increases in the area sown to cereal crops will make virtually no contribution to future increases in cereal production. In fact total area sown to cereals is likely to fall, except in Southeast Asia.[2] Second, because cereal crops in Asia have experienced an unusually high rate of yield gains in the past 25 years, more modest progress must be expected in the future. As noted earlier, the effects of these trends will be lessened partly by slower growth in demand for food grains. Nonetheless, CIMMYT projects that demand for wheat will grow at 3% annually in the 1990s; this demand must be met by increasing yield per unit area or by increasing imports (CIMMYT 1989).

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2 Cereal area is falling due to crop diversification and non-farm uses of agricultural land.

Figure 1. Growth Rate of Cereal Production and the Contribution of Area and Yield Growth in Asia by Decade.

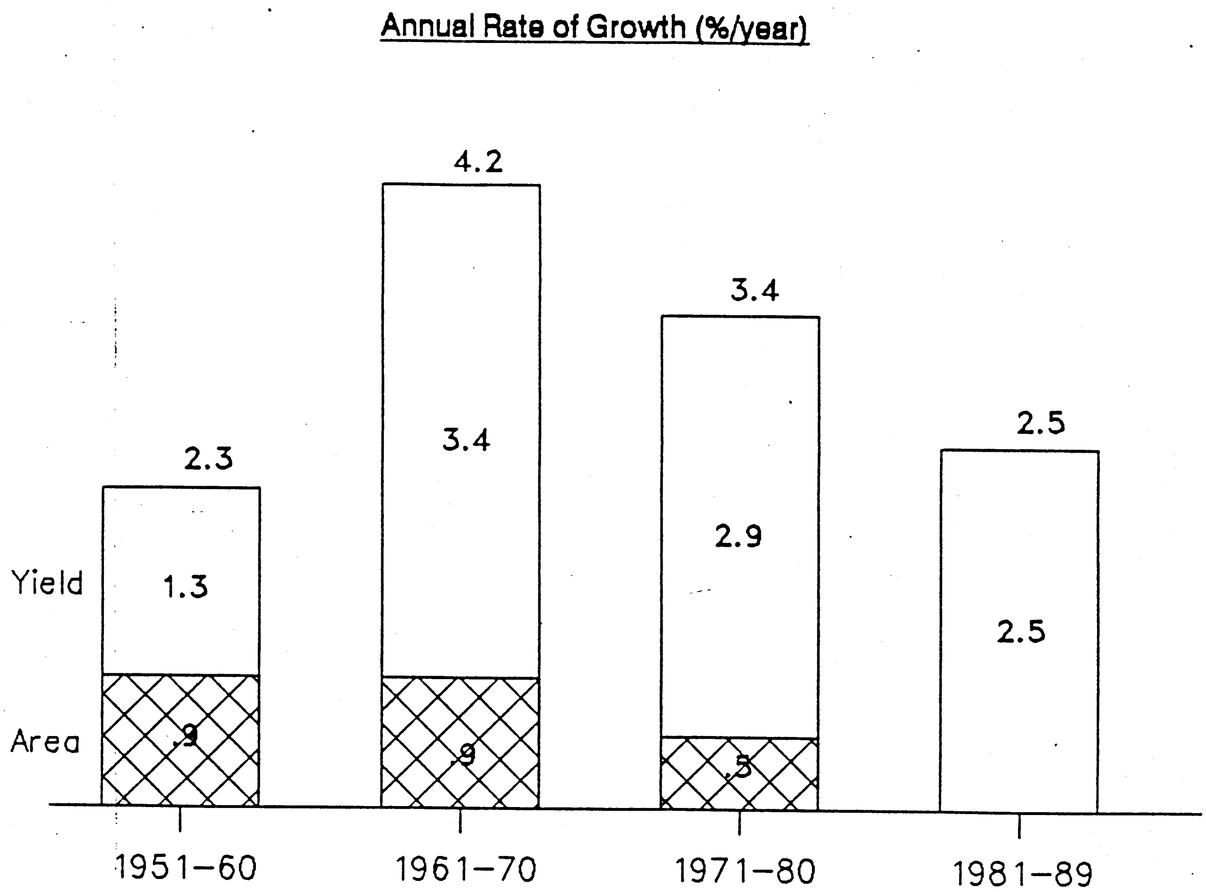
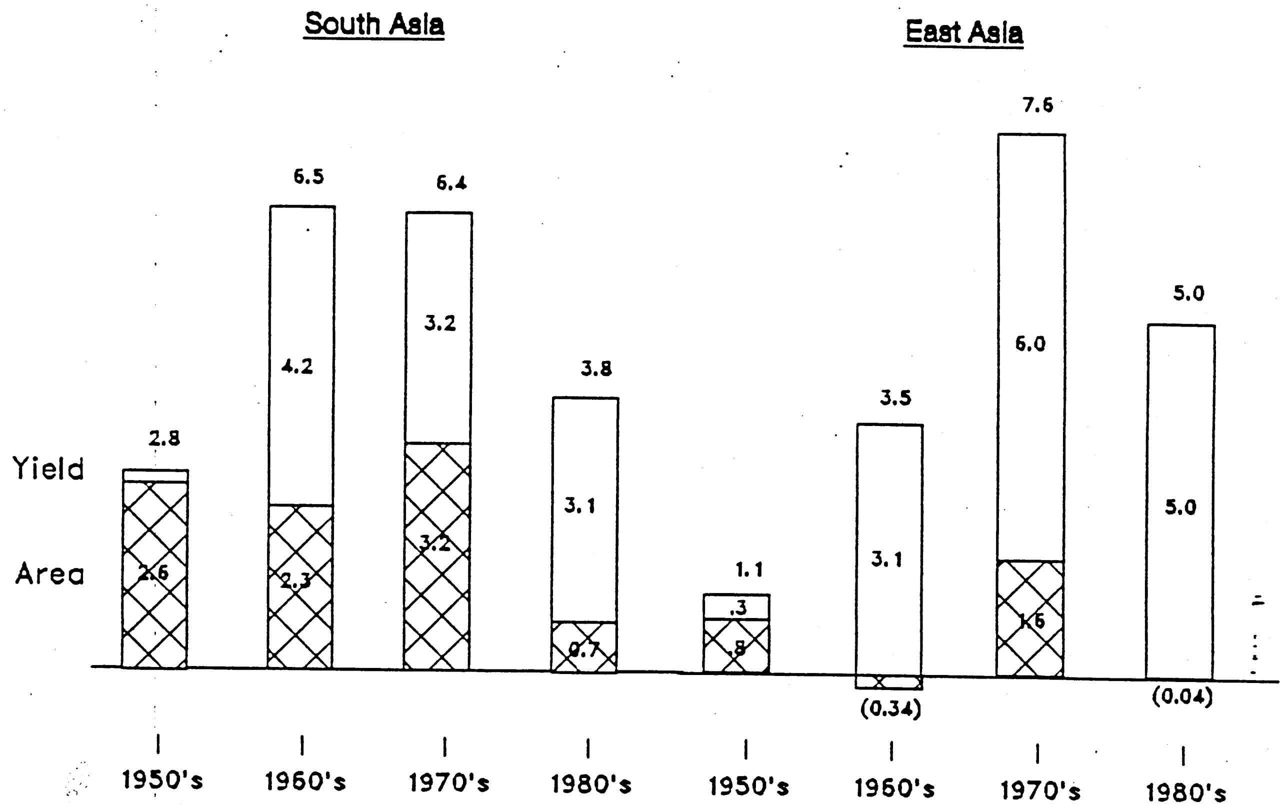


Figure 2. Growth Rate of Wheat Area, Yield and Production by Decade.



## A Conceptual Framework for Analyzing Technical Change in Asian Agriculture

The recent history of agricultural development in Asia's land-intensive systems can be viewed as a continuum of technical and institutional change. The various stages in the evolution of agricultural development can be evaluated in terms of the sources of gains in productivity, the institutional support for technical change, and the implications for sustainability. Each of these aspects of agricultural change is briefly discussed in the sections that follow.

### Stages of Technical Change

Technical change in land-intensive systems over the past few decades can be divided into four stages:[3]

1) The pre-Green Revolution phase, when gains in productivity per unit of land area were modest. Instead, expansion in area planted to food grains played the chief role in increasing food production (Phase I).

2) The Green Revolution phase, when a technological breakthrough in the form of new, high-yielding varieties (HYVs) responsive to inputs provided the potential to dramatically increase the productivity of land (Phase II).

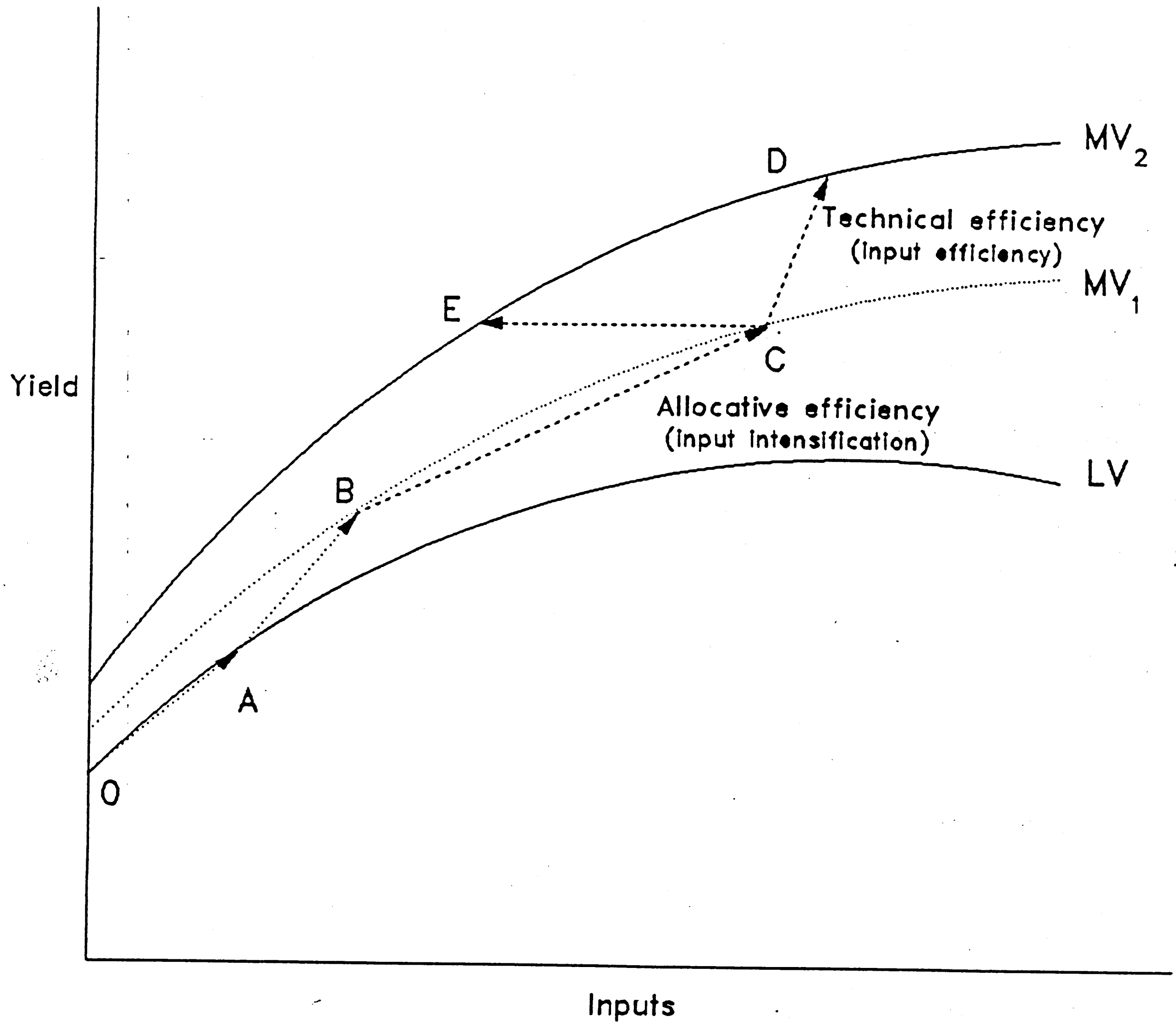
3) A post-Green Revolution phase, beginning after the widespread adoption of HYVs, when intensification of input use, especially chemicals, substituted for increasingly scarce land for agriculture (Phase III).

4) A post-Green Revolution phase, beginning after input use has reached high levels. In this stage farmers' experience with the new technology, together with changes in support institutions and policies, have evolved to allow improved skills and information to substitute for input use (Phase IV).

Figure 3 depicts these phases in the framework of a production function. The introduction of HYVs shifts the production function sharply upwards to $MV_1$, and increases the response to inputs, especially fertilizer and water. Adoption of modest levels of these complementary inputs accompanies the adoption of HYVs. Moreover, for various reasons farmers cannot exploit the full benefits of the new technology immediately and operate at B below the technological frontier, $MV_2$. In the next phase, when input use intensifies, farmers move along the new production function by using higher levels of complementary inputs. This phase may be viewed as a

3 In practice these stages often overlap. For a fuller discussion of these issues, see Byerlee (1990a).

Figure 3. Simplified View of Stages of Productivity Change in Land Intensive Agriculture.




| | | | |
|---|---|---|---|
| OA | Phase I | Expansion of land area | |
| AB | Phase II | Land saving technical breakthrough | |
| BC | Phase III | Input intensificacion | Post-Green Revolution |
| CD, CE | Phase IV | Input efficiency | Post-Green Revolution |

time of improving allocative efficiency as the marginal value of productivity of each input approaches its acquisition price. Finally, as farmers approach allocative efficiency, they move toward the production frontier by employing better information and skills to increase the efficiency with which they use inputs. (In other words, gains in productivity result more from increased technical efficiency than from improved allocative efficiency.) Input use may expand only modestly during this stage if farmers move from C to D. Alternatively, depending on the institutional and policy environment, another path might be from C to E, where yields are held constant, but input use is reduced. In any event, yield gains in this stage will be much less impressive compared to gains in previous stages, although increases in total factor productivity may be quite rapid.

**Evolution of Institutional and Policy Support for Technical Change**

To be successful, each stage in the process of technical change should be accompanied by appropriate changes in institutions and policies. For example, during the initial stage of technical change the contribution of the local research system is limited if the new technology (for example, a new HYV) is imported. However, once this technology is adopted, strong local crop breeding programs are required to 1) maintain the gains that have already been made, especially where new varieties' resistance to pests and diseases breaks down and 2) tailor varieties to more specific niches determined by agroclimatic variables and cropping patterns. In contrast, during this phase and the input intensification phase, research on crop and resource management may be relatively unimportant. Rather, the adoption of HYVs, the learning process of farmers as they use the new technology, and institutional improvements in the input distribution system contribute to increasing levels of input use. However, moving toward the input efficiency stage requires strong crop management research programs capable of developing site-specific crop management information and facilitating the substitution of information for input use. (One example of substituting information for inputs is integrated pest management, which require considerable information and skill to execute successfully.) At the same time, in this phase of technical change the institutions responsible for disseminating information, such as extension organizations, must evolve rapidly to serve farmers' needs for more technical information and skills.

Finally, the price policy environment must also adjust to each phase of technical change. The early stages of technical change are often characterized by stabilization of producer prices for food grains and by subsidization of input prices. These policies aim to provide incentives for using inputs more intensively and overcoming market imperfections arising from perceived risk, scarce capital, and the costs of learning to use the new technology. Removing these subsidies in the later stages of technological evolution provides one incentive for using inputs more efficiently and possibly moving from C toward E in Figure 3.

**Sustainability**
A third important element of changes in productivity is the sustainability of agricultural production systems. The term "sustainability" has been given varied interpretations. This paper uses a definition adapted from Lynam and Herdt (1989) and CIMMYT (1989): sustainability is the ability to achieve long run stable gains in productivity while maintaining or even enhancing the quality of the agricultural resource base. Continued productivity increases are clearly a critical element of a sustainable agriculture.

Problems of maintaining the resource base can be divided into two categories, depending on their ease of solution over time. Some problems are more easily amenable to technical solutions. Nutrient "mining," for example, can usually be rectified by adding secondary nutrients (such as potassium) or micronutrients. Other problems cannot be solved without significant institutional or policy changes, which usually require a longer time to implement. For example, solving the problem of overexploitation of underground aquifers may require significant changes in legal rights to install new tubewells and perhaps the removal of subsidies on energy prices.

Sustainability problems also differ depending on the investment cost needed to solve them. This cost often increases exponentially as the problem becomes more severe. At some point the costs of remedial action may become so high that the deterioration of the resource base is essentially irreversible. Examples might include severe soil erosion or salinization. Hence an early diagnosis of sustainability problems is often a necessary condition to finding cost-effective solutions.

The working definition of sustainability presented here also emphasizes the stability of a system, especially the ability to withstand external shocks. Shocks may result from abrupt changes in the economic environment, such as a sharp rise in the price of a key input such as fertilizer, or in the natural environment, such as the advent of a new strain of a disease, or a severe drought.

## The Technological Breakthrough and Input Intensification

Changes in productivity in wheat-based systems of Asia over the past three decades have followed the stages enumerated above. Most of the productivity gains have come about through the release of new HYVs accompanied by increased intensification in the use of inputs, especially fertilizer and water. The use of each of these inputs is now high in many places, as data from advanced rice-wheat production areas indicate (Table 1). The following summary of changes in the use

**Table 1. Input use and yields in rice-wheat systems of advanced districts of South Asia**

| | Pakistan (Sheikhapura/ Gujranwala, Punjab, 1990) | India (Ludhiana Punjab, 1988) | Bangladesh (Dinajpur, 1990) |
|---|---|---|---|
| Percent wheat planted after rice | 73[b] | 73 | 93 |
| Cropping intensity (%) | 167 | 182 | na |
| Mean planting date | 29 Nov.[b] | 15 Nov. | After 15 Dec. |
| Seed rate (kg/ha) | 98[b] | 99 | 147 |
| Weighted mean age of variety (years)[a] | 9.7 | 4.4 | 12.5 |
| Percent area planted to dominant variety | 59 | 67 | 51 |
| Average fertilizer applied (kg/ha) | | | |
| N | 82 | 138 | 72 |
| $P_2O_5$ | 49 | 74 | 25 |
| $K_2O$ | 0 | 4 | 25 |
| Total | 131 | 216 | 152 |
| Percent apply herbicide | 35 | 65 | 0 |
| Average yield (t/ha) | 2.40 | 3.93 | 2.70 |

a Measured in years from varietal release.

b Data are for previous year(s).

Source: Pakistan - Agricultural Economics Research Unit, Faisalabad (personal communication).
India - Punjab Agricultural University (personal communication).
Bangladesh - Saunders (1990).

of inputs suggests that more intensive use of inputs will make a smaller contribution to production increases in the future.

**High-Yielding Varieties**

The rapid diffusion of modern semidwarf wheat varieties (that is, HYVs) in South Asia is well documented (e.g., Dalrymple 1986). For the purposes of this paper, two aspects of the diffusion process should be noted. First, the use of HYVs expanded particularly rapid in the irrigated areas of South Asia, and the adoption process was essentially complete by the late 1970s (Figure 4). During the 1980s, only minor gains have been made by the substitution of HYVs for local varieties.[4]

A second important feature of the diffusion of HYVs in Asia is that wheat breeders have substantially increased efforts to develop locally adapted varieties and maintain disease resistance to evolving pathogens (especially rust pathogens). For example, the average number of wheat varieties released annually in India rose from 2.6 in the 1960s to 3.4 in the 1970s, and then jumped to 7.2 between 1981 and 1985. At the same time researchers have made steady improvements in the genetic yield potential of newer wheat varieties at the rate of 0.5-1.0% per year (Byerlee 1990b; Waddington et al. 1986). Although adoption of newer varieties has often been slow (Heisey 1990), most farmers in the main wheat belt of India and Pakistan have replaced their varieties at least twice since adopting the original Green Revolution varieties in the late 1960s. The superior disease resistance and higher yields of the newer varieties have helped stabilize yields and have provided good returns to economic investments in wheat breeding (although lower than the returns to the original development of HYVs) (Byerlee 1990b).

**Irrigation**

Increasing supplies of irrigation water made a major contribution to increasing wheat area and yields in the 1960s and 1970s in much of Asia. For example, in India the percentage of wheat area under irrigation grew from 33% in 1961 to 75% in 1988 as irrigation facilities became available on formerly rainfed land (Figure 5) and as wheat substituted for other crops on irrigated land. Irrigation alone may explain almost half of the increase in Indian wheat production over this period (Ahluwalia 1989). However, after irrigation facilities were developed on the less expensive and less difficult sites, the expansion of irrigated area slowed in the 1980s (Table 2). Rapid installation of tubewells has also meant that groundwater accounts for an increasing share of the total irrigation water supply (Figure 6).

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4 The major exception to this trend is seen in China, where the rapid adoption of semidwarf varieties began more than a decade after the impact of the Green Revolution began to be felt in South Asia (Dalrymple 1986; CIMMYT 1989).

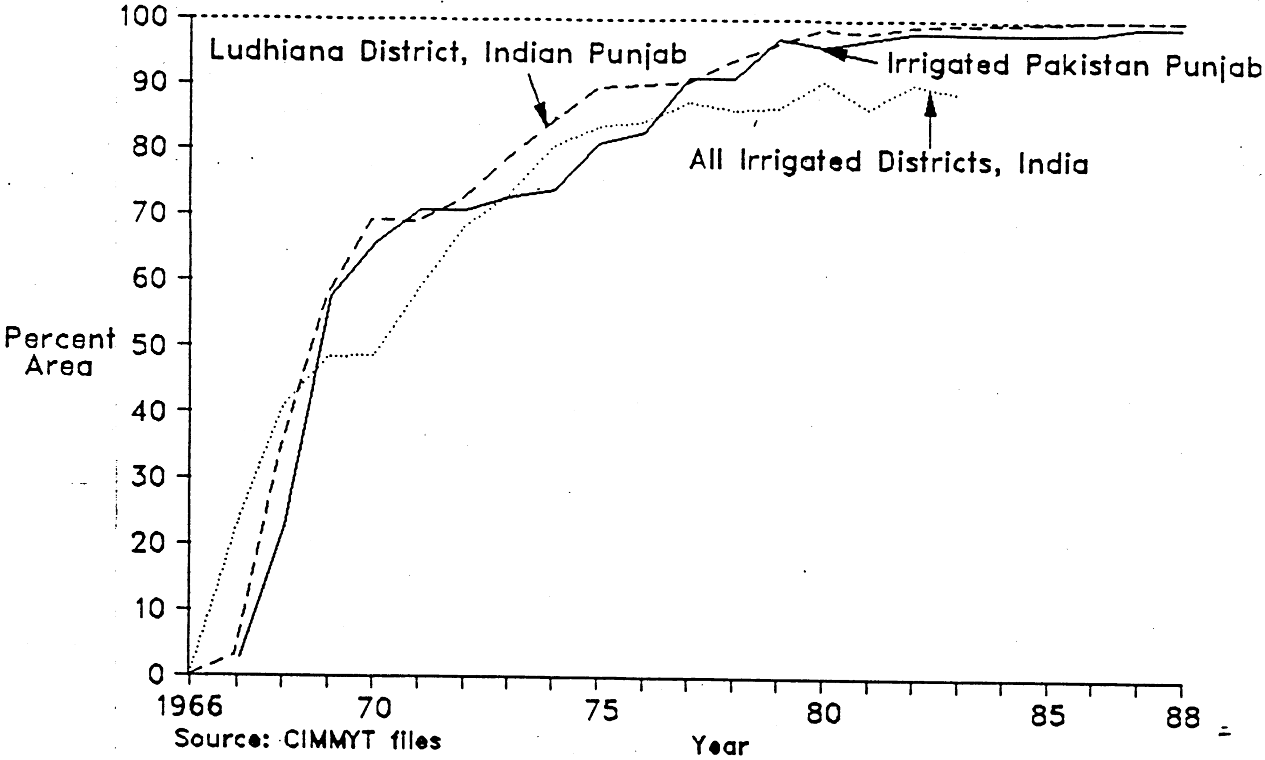


Figure 4. Percent Area Sown to Semidwarf Wheat Varieties in Irrigated Areas of India and Pakistan.

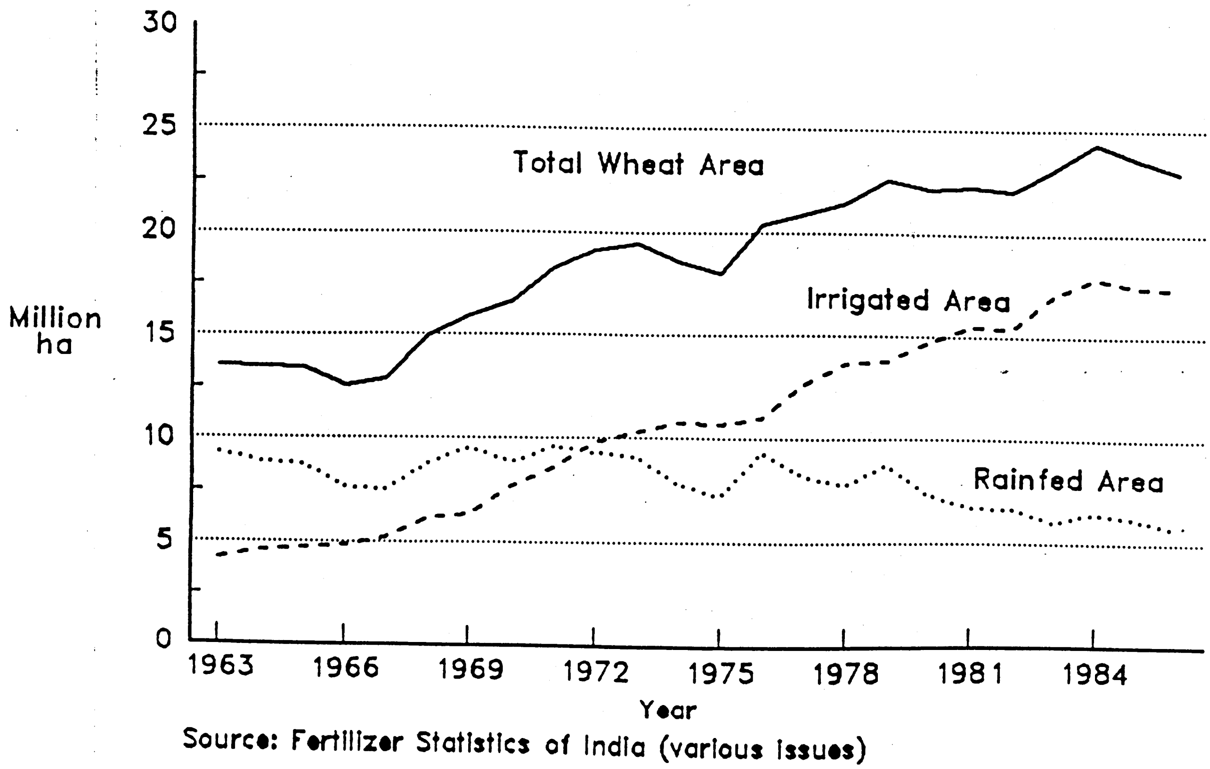


Figure 5. Trends in Rainfed and Irrigated Wheat Area in India, 1963–1986.

Table 2. Rate of growth of total irrigated area in Asia, 1965-84

| Period | South Asia | China | All Asia[a] |
|---|---|---|---|
| | (% per year) | (% per year) | (% per year) |
| 1965-69 | 2.7 | 2.9 | 2.5 |
| 1970-74 | 1.9 | 2.9 | 2.1 |
| 1975-79 | 2.2 | 0.0 | 1.9 |
| 1980-84 | 1.0 | 0.0 | 0.7 |
| 1965-84 | 2.1 | 1.2 | 1.6 |

Source: Levine et al. (1988).

[a] includes Southeast and West Asia.

## Fertilizer

While increases in the area sown to HYVs and the proportion of irrigated area tended to level off in the 1970s, fertilizer use continued to expand rapidly in the 1980s, a period of input intensification in much of South Asia (Figure 7). Only in the most advanced areas, such as the Indian Punjab, is fertilizer use on wheat levelling off at around the recommended level of 200 kg of nutrients per hectare (Figure 7). Increasing fertilizer use, of course, leads to diminishing returns: the marginal grain-to-nutrient ratio, which was around 15:1 when HYVs were first adopted, is now as low as 5:1 in the Punjabs of India and Pakistan (Grewal and Rangi 1983; Aslam, et al. 1989).[5]

The expansion in fertilizer use was achieved in three ways: by farmers increasing the area fertilized; applying nutrients other than nitrogen (especially phosphorus and sometimes potassium); and applying higher doses of nitrogen. Adoption of nitrogenous fertilizer was essentially completed by the mid-1970s on irrigated wheat (Desai 1986), and phosphorus was also rapidly adopted in the 1970s in most areas. Recent surveys also indicate widespread use of potassium in Bangladesh (Table 1).

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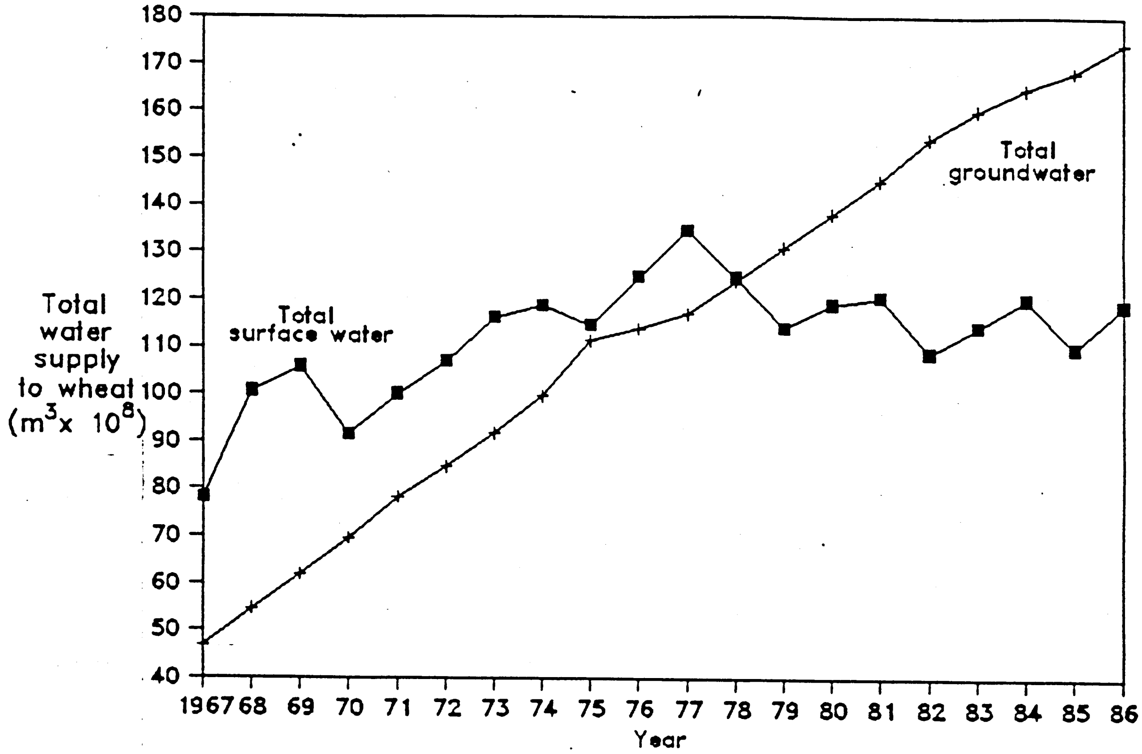
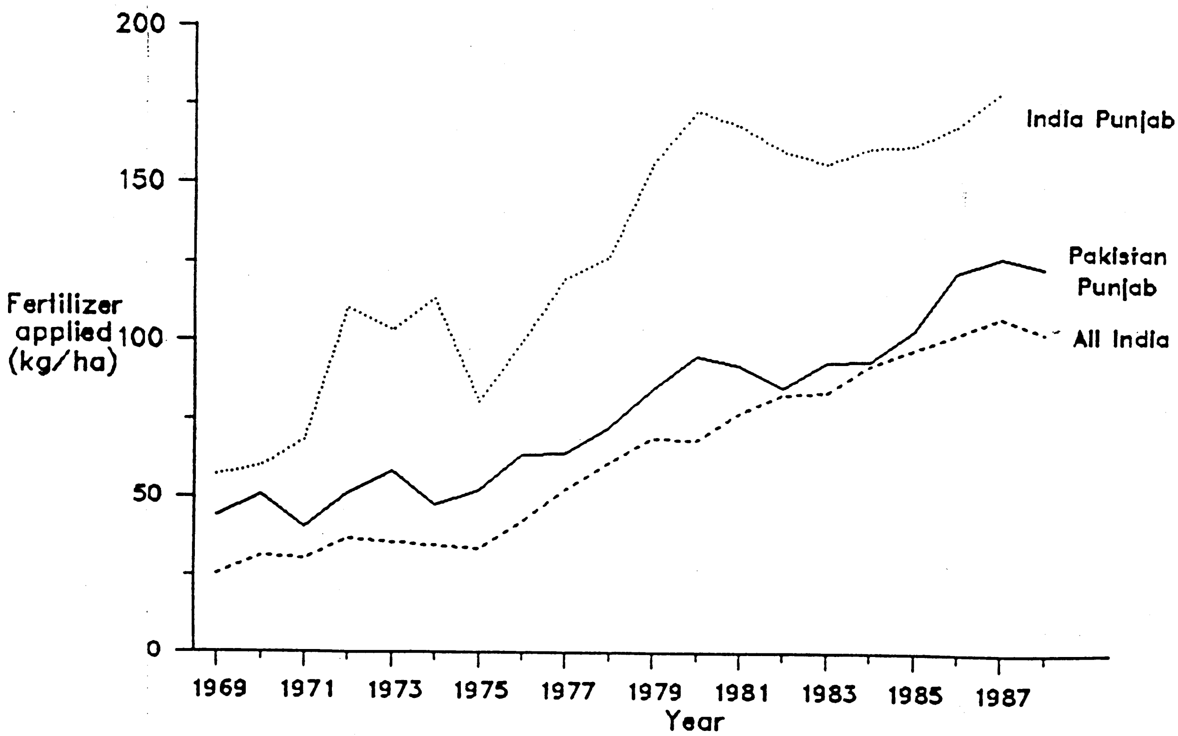
5 The ratio of 5:1 is an average for all nutrients. Higher ratios are achievable for some nutrients indicating the need for more balance fertilizer doses.




Note: See Byerlee and Siddiq (1990) for assumptions used in calculations.

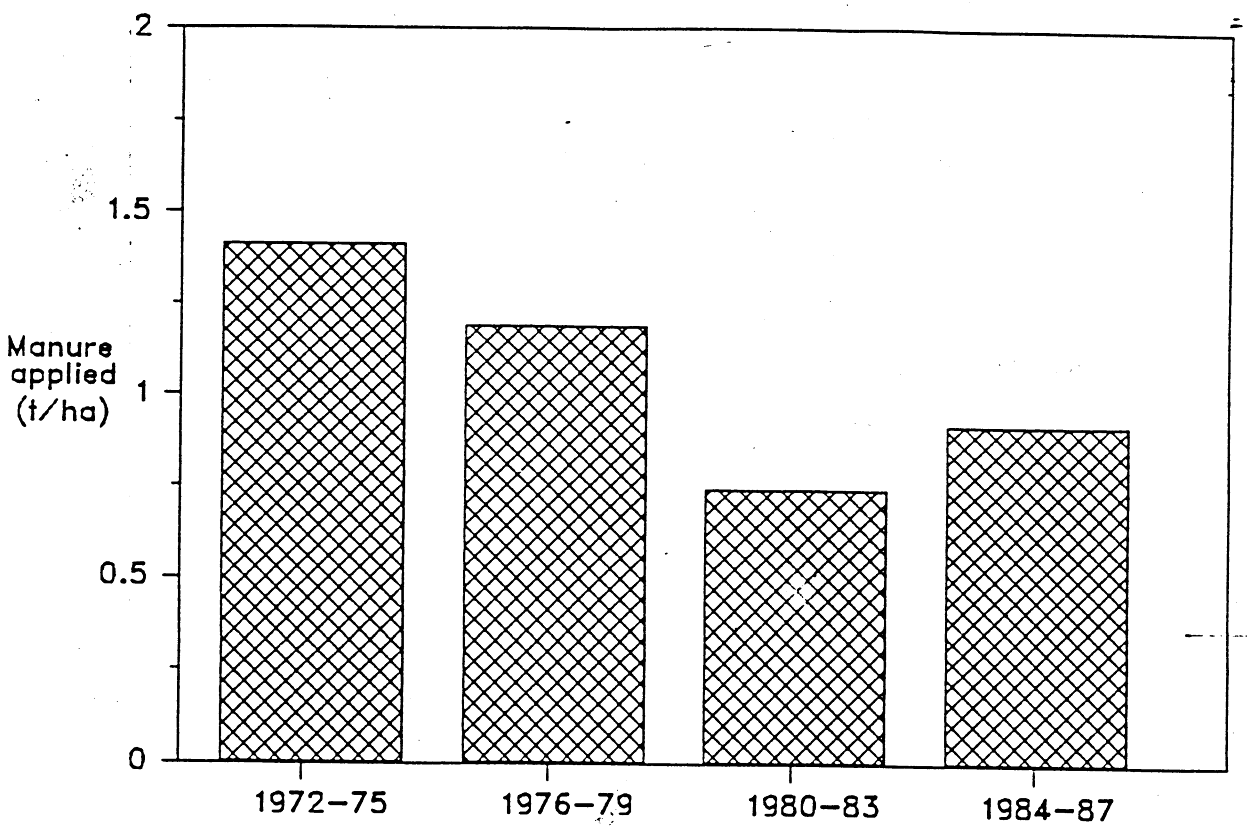
Figure 6. Trends in Water Supply to Wheat, Punjab, Pakistan, 1967–86.




Source: CIMMYT estimates based on rabi (winter) fertilizer offtake.

Figure 7. Estimated Fertilizer Use (kg nutrient/ha) on Wheat in South Asia.

At the same time, accumulating evidence indicates that the use of organic matter is declining in the intensive irrigated production systems of South Asia. This decline is observed in comparative survey data across time (Byerlee and Siddiq 1990; Sidhu and Byerlee 1990) (Figure 8) and can be deduced from balance sheets for recycling organic manure and crop residues (Chopra 1990). Farmers appear to be applying less organic manure because tractors are increasingly substituted for bullock power, more organic manure must be used as cooking fuel, and costs of the labor-intensive activities of collecting and applying manure are high. Even in China, which has a long history of heavy use of organic manures, application of manures is declining for similar reasons, as chemical fertilizers become more readily available.




Source: Sidhu and Byerlee (1990)

Figure 8. Trends in Organic Manure Use in Wheat Production, Punjab.

**Pesticide Use**

Contrary to popular opinion, the application of pesticides on new wheat varieties is minimal in most areas (except for very low doses commonly used to treat seed in many areas), because of the high levels of disease resistance bred into HYVs. The major exception is the use of herbicides. Although farmers use various cultural practices (rotation, delayed planting, and hand weeding) to control weeds in irrigated wheat, these practices have not prevented the rapid spread and build-up of some weeds in intensive cropping systems. The weed Phalaris minor is an especially persistent problem in the rice-wheat systems of South Asia. However, beginning in the early 1980s, herbicide use became common in the Indian Punjab and quite recently this practice spread rapidly to other areas of northern India and Pakistan. In these areas, chemical control has proven to be a critical part of an integrated weed management strategy, giving a significant boost to wheat yields in rice-wheat systems (Aslam et al. 1989).

**Mechanization**

Parallel with the changes in biochemical technology, agricultural mechanization has proceeded rapidly throughout Pakistan and much of northwestern India. The greatest change has occurred in land preparation and planting. For example, in Pakistan and the Punjab of India, tractors are used on as much as 75% of the wheat area. Various policies (e.g., subsidized credit) and rising costs of labor and draft power have promoted these changes. The evidence generally indicates that increased mechanization has usually saved labor rather than served as means to intensify land use (Binswanger 1978; Tetlay et al. 1990). Adoption of suitable tillage and planting implements has lagged far behind the adoption of tractors. Farmers' use of inappropriate implements may be contributing to soil compaction problems and poor plant stands as well as a long turnaround time between crops.

**The Current "Yield Gap"**

Average yields of irrigated wheat in South Asia (2-2.5 t/ha) suggest that a considerable gap between potential yields and farmers' yields has yet to be exploited, especially since researchers commonly quote a yield potential of 6-7 t/ha. In advanced areas such as in the Indian Punjab, however, the yield gap is relatively small and declining over time (Figure 9). There is evidence that this gap has narrowed as variation of yields and input use across farmers has diminished, so that the difference between the lowest and highest yields in farmers' fields has decreased (Singh et al. 1987). The average yield in the Indian Punjab is now 90% of yields in the most advanced district, Ludhiana, compared to 66% in 1966 (Figure 9). Wheat yields in the Punjab are now 70-80% of yields obtained on experiment stations--a figure close to the equivalent gap for maize yields in Illinois (Herdt 1988). This suggests that in these advanced areas the economically recoverable gap is quite small.

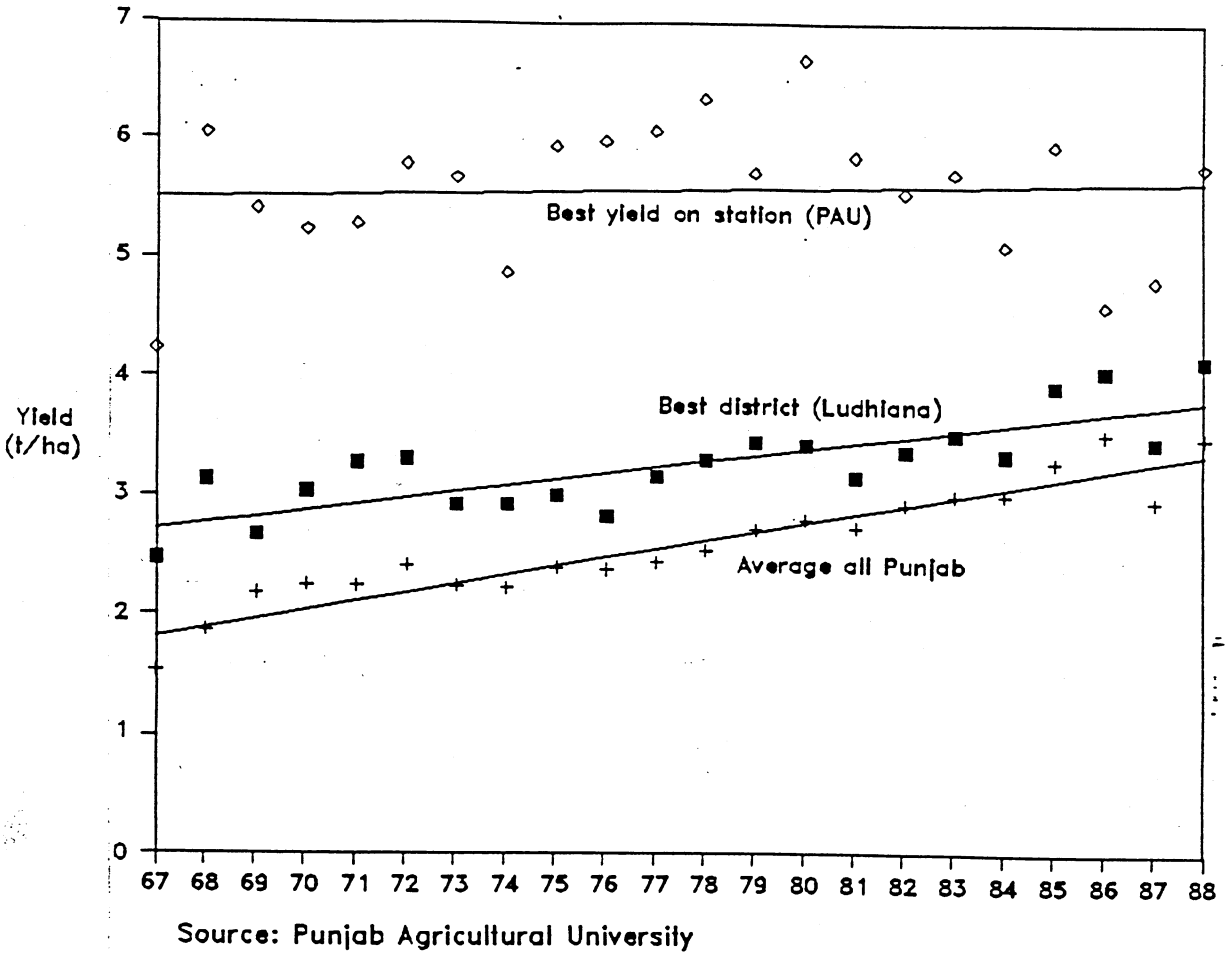



Figure 9. Farmer Yields and Potential Yield of Wheat, Punjab, India.

By contrast, in the Punjab of Pakistan, yields of irrigated wheat remain at about 2 t/ha despite the use of moderate to high levels of inputs. On-farm experiments suggest an economically recoverable gap of 1-1.5 t/ha (Aslam et al. 1989), much less than the amount commonly cited by research administrators and policy makers, but nonetheless significant. Factors that can close the yield gap in the short term are timely planting (e.g., through zero tillage), better plant stand, improved weed control, and more balanced fertilizer applications in terms of the mix of nutrients applied.[6] However, gains from adopting these practices will provide smaller yield increments and often be less profitable than gains from adopting the original seed-fertilizer technology, and hence are more difficult to achieve.

6 It is likely that a yield gap of similar magnitude exists in irrigated wheat areas of northeastern India and Bangladesh, where yields are also below 2 t/ha (Saunders 1990).

The evidence presented above suggests that in much of the irrigated wheat-based systems of South Asia further efforts to intensify the use of inputs will give much lower returns than in the recent past, especially in the more advanced areas where input use approximates levels of inputs used on research stations. Nonetheless, in many of these areas, there appears to be considerable potential to close the "technical efficiency gap," which is estimated at about 30% in many settings in South Asia (see Ali and Byerlee, forthcoming 1990, for a review).[7] However, this will require important institutional changes that are discussed below.

## Increasing Intensity and Specialization of Cropping Systems

As input use has intensified in irrigated areas, a broad-based increase in cropping intensity at a steady 0.5-1.0% per year has also occurred. Cropping intensity in advanced areas of the Indian Punjab now approaches 200%. Crop intensification reflects growing land scarcity and has resulted from the adoption of HYVs, which mature earlier than the traditional varieties they replaced, accompanied by improved supplies of irrigation water. The increase in cropping intensity has also been achieved by growing wheat in specialized rotations that have come to dominate much of the subcontinent. These rotations generally involve growing wheat after a cash crop planted in the summer season, such as cotton, rice, or soybeans. Such rotations also reflect the growing commercialization of agriculture, as they have partly replaced the traditional, more diversified cropping patterns emphasizing coarse grains, pulses, and oilseeds. For example, the rice-wheat cropping pattern, now estimated to occupy some 10 million hectares in South Asia, has spread rapidly in the past two decades. Rice area has increased sharply in the northwestern Gangetic Plain (e.g., in the Indian Punjab) and wheat has been widely adopted as a short-season winter crop in the eastern Gangetic Plain (Hobbs 1988).

It is in these newer rotations of wheat following rice, cotton, or soybeans that problems arising from conflicts in planting and harvesting dates have become most acute. Wheat planting is commonly delayed across most of the irrigated wheat belt of South Asia. In India, an estimated 40% of wheat is planted after the optimal period, with the most serious delays occurring in the rice-wheat areas (Tandon 1988). In Pakistan, survey data indicate a steady progression over time toward later planting in both major cropping systems--rice-wheat and cotton-wheat (Figure 10). In the rice-wheat system, delays in wheat planting sometimes reflect the use of longer maturing rice varieties, although in most cases wheat planting is delayed because rice is planted late and because of the long turnaround between harvesting

7 That is, yields are 30% below the potential (as determined by the best yields achieved by farmers) for the same level of inputs.

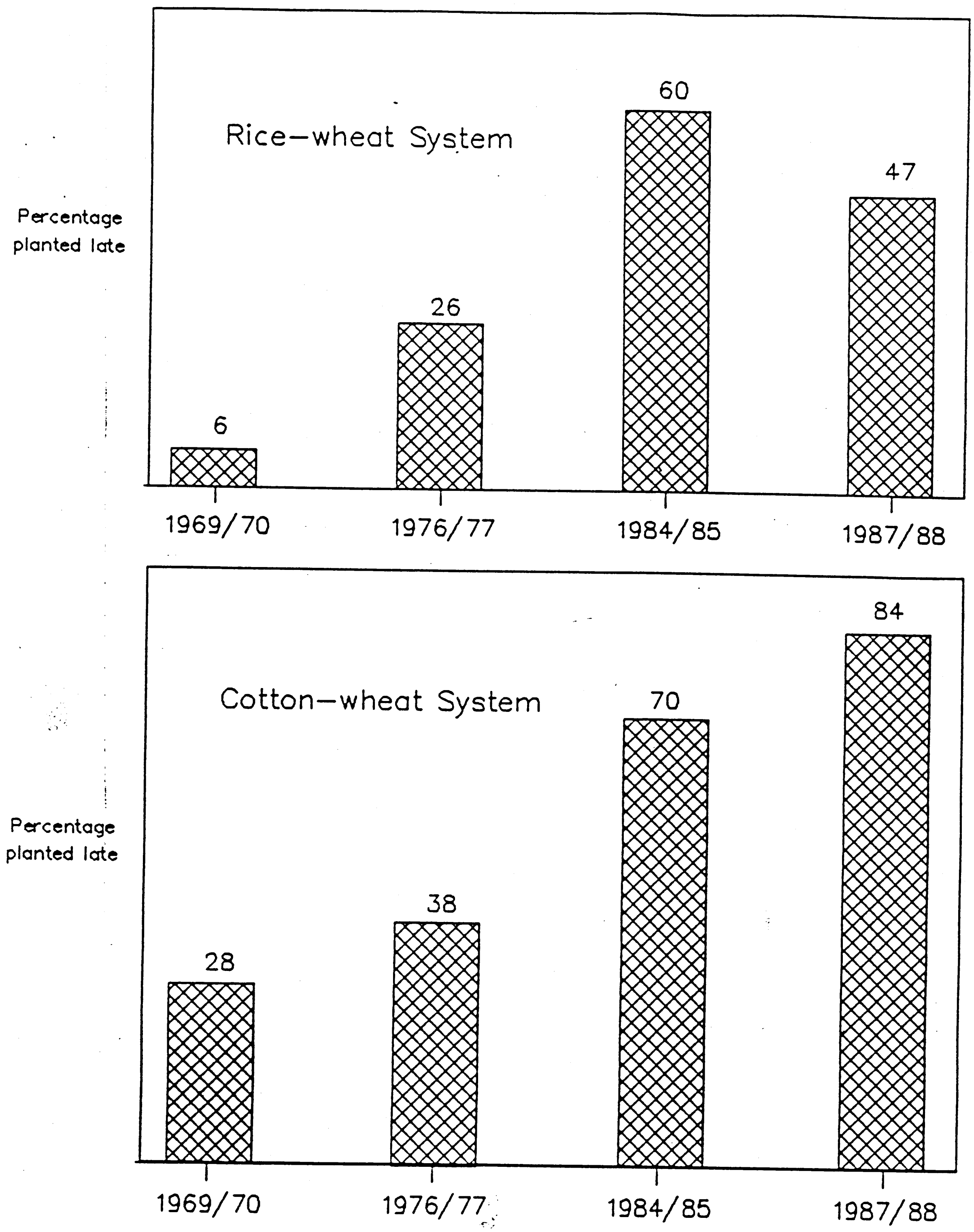



**Figure 10. Percent Wheat Planted Late (after 1 December) in the Punjab of Pakistan.**

Source: S. Bashiruddin (personal communication) rice and planting wheat in heavier soils. Delayed wheat planting is generally estimated to lead to a loss of 1% in yield per day beyond the optimum planting date. Such conflicts may be a major cause of the low and declining productivity of wheat in many systems. However, reduced wheat yields caused by conflicts in the cropping system do not necessarily imply that the system as a whole has a sustainability problem, since cropping intensity has increased by adoption of these cropping systems.

In recent years, some progress has been made toward resolving these conflicts. Plant breeders now give priority to developing earlier maturing varieties of rice, cotton, and soybeans. Released in the late 1980s, these varieties have probably arrested and perhaps even reversed the tendency toward late planting (Byerlee et al. 1987; Sharif et al. 1990). Breeders also screen for varieties that perform well when planted late and are beginning to obtain positive results (Saunders 1990).

Nonetheless, increased crop intensification and specialization may have additional costs. Weeds and other pests can build up because farmers practice the same rotation continuously, without a break crop. Also, crops grown in a system, such as rice and wheat, may have different needs with respect to soil physical structure and drainage. For example, in the rice-wheat area of Pakistan's Punjab, yields from fields planted continuously to wheat for three or more years (the dominant rotation) show a significant negative tendency because of these problems (Byerlee et al. 1984).

## Emerging Issues in Sustainability

### Is There Evidence of a Sustainability Problem?

Any measure of sustainability should consider changes in productivity, maintenance of the quality of the resource base, and the overall stability of the system being analyzed. If productivity is defined narrowly in terms of yield per unit area, then lack of sustainability would be identified with a decline in yields over time. This kind of decline is not always easy to detect, especially in a variable environment. In the particular case of irrigated wheat-based systems, such a decline can be documented in only a few cases.

A more meaningful measure of productivity is total factor productivity (TFP): that is, the change in output relative to the change in all inputs. This measure is especially appropriate for assessing sustainability problems in Asia, where biological and chemical inputs have rapidly been substituted for land. Unfortunately TFP is difficult to measure because of the extensive data requirements. A restricted case is to examine trends in yields over time for fixed levels of all inputs (declining yields for the same input levels are an indicator of a sustainability problem). Data from long-term experiments are most appropriate for measuring such changes.

Substantial information is available from long-term experiments in India over about 15 years, although very little information is available from other South Asian countries. The results of these trials indicate that consistent patterns of declining yields may be quite specific to sites and crops, depending on soil type, cropping pattern, and level of input use (IARI 1989). However, even when the recommended level of fertilizer is used, significant yield declines (at least for rice) have been observed in the rice-wheat system at most sites (including Pantnagar--see Figure 11 --and Barrackpur in India and Bhairahawa in Nepal) (IARI 1989; P. Hobbs, pers. communication). Declining yields are generally not evident in wheat (Figure 11) although, at 4 t/ha or less, wheat yields are low considering the high level of inputs and management used in the experiments. In addition, since newer wheat varieties were included in these trials in recent years, one would expect to see a positive yield trend because of the improved yield potential of the newer wheats.[8] Hence, correcting for the change in variety may also reveal a yield decline in wheat. In most experiments, declining yields seem to be arrested by applying higher levels of macronutrients (especially nitrogen), using organic manures, or adding sulfur or micronutrients (especially zinc) (IARI 1989).

Another approach to inferring changes in TFP is to examine changes in farmers' yields in relation to changes in specific, readily measurable inputs. Byerlee and Siddiq (1990) use this approach to decompose yield changes in the Punjab of Pakistan into effects on yield from: 1) substituting HYVs for local varieties, 2) adopting newer HYVs, and 3) increasing the fertilizer dose (Table 3). Using conservative agronomic assumptions about each of these effects, Byerlee and Siddiq found a significant negative residual, which pointed to some factors that tend to reduce yields over time. Indeed, yields of HYVs in the Punjab of Pakistan have not changed in nearly two decades, despite the adoption of newer HYVs and a tripling of the fertilizer dose (Figure 12).

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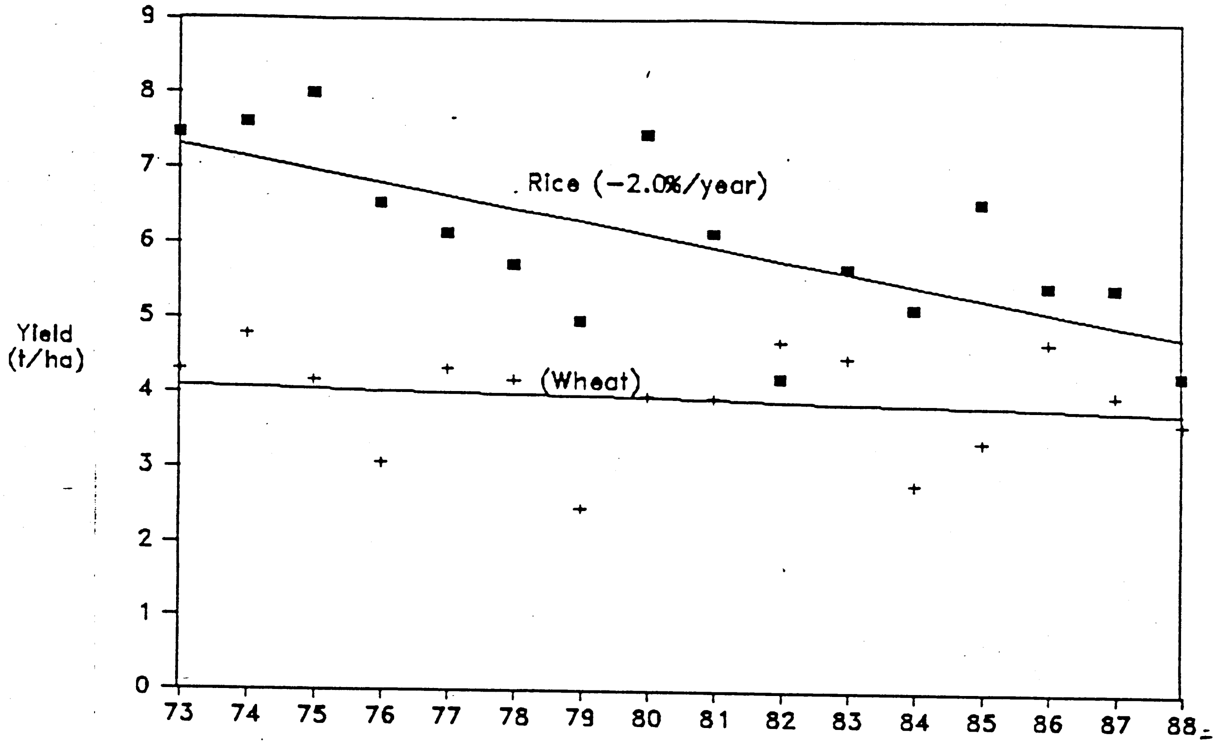
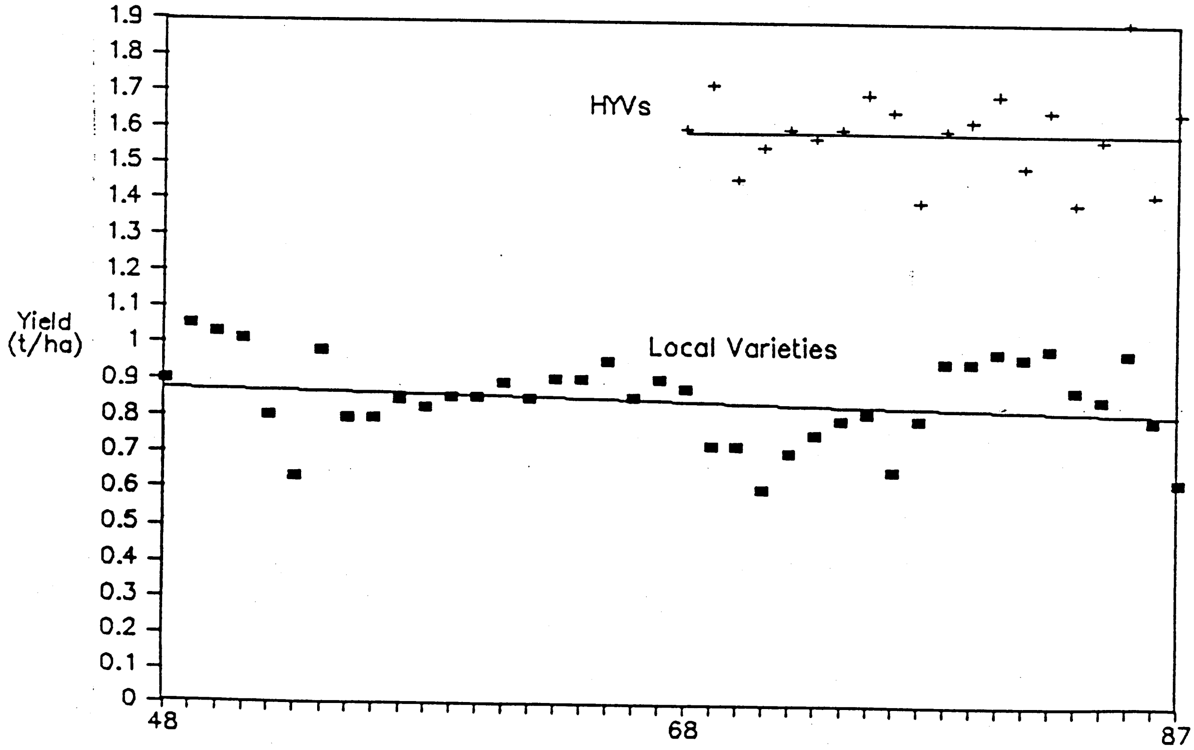
8 A significant positive yield trend has been observed in long-term trials in some sites such as Ludhiana in the Punjab (IARI 1989).




Source: G.B. Pant University, Patnagar

**Figure 11. Rice and Wheat Yields, Long Term Trial, Pantnagar, India.**




Source: Calculated from Agricultural Statistics of Pakistan (varios issues)

**Figure 12. Trends in Yields of Local and High–Yielding Varieties, Punjab, Pakistan, 1948–87.**

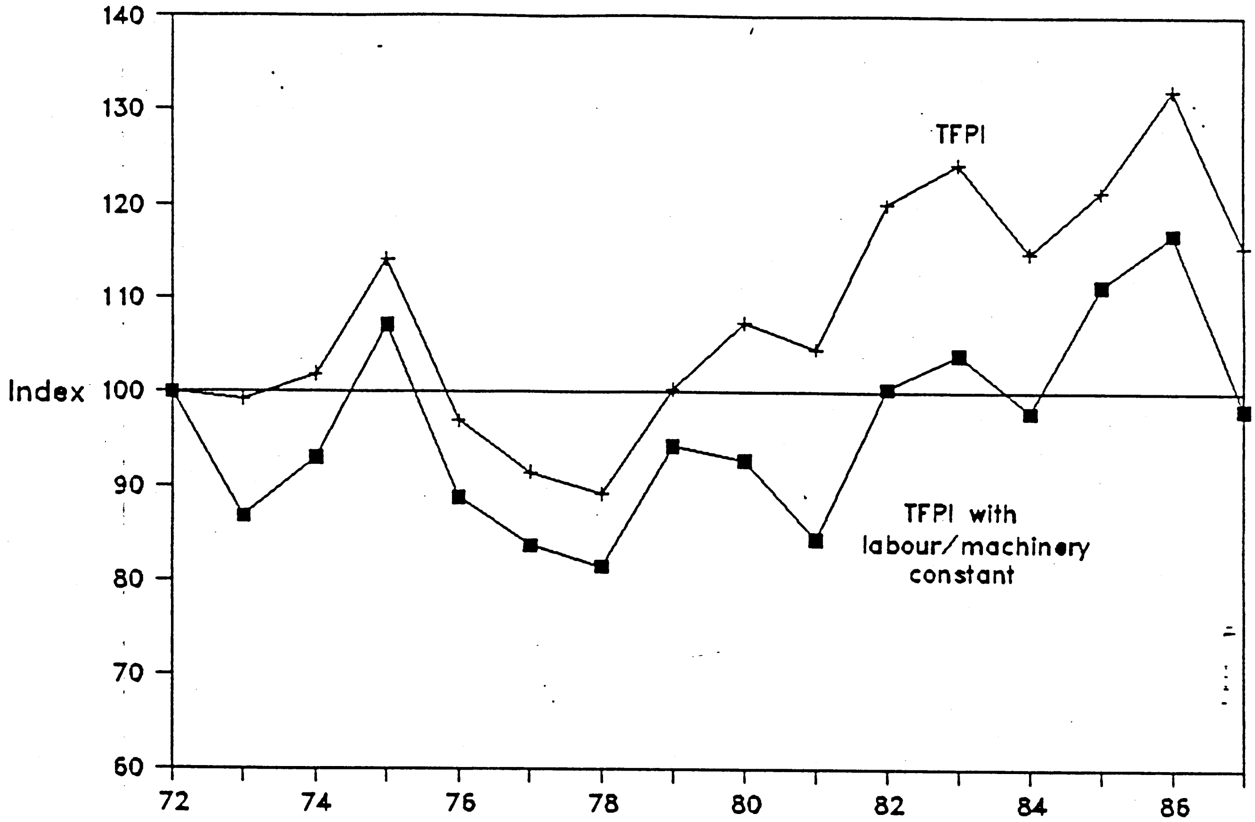
**Table 3. Expected and actual gains in wheat yields in the irrigated Punjab, 1972-1986**

| Source of gain | Effect (kg/ha) |
|---|---|
| 1. Switching from old to new varieties on remaining 33% of area. | 141 |
| 2. Genetic gains in yield of newer varieties (0.75%/year) | 138 |
| 3. Increased fertilizer use of 73 kg/ha at grains nutrient ratio of 8.1 | 446 |
| Total projected gain | 725 |
| Actual gain | 375 |
| Unexplained | -350 kg/ha |

Source: Byerlee and Siddiq (1990).

The most comprehensive approach is to measure the TFP over time, a data-intensive exercise. Such data exist for the Indian Punjab, and Sidhu and Byerlee (1990) calculated an average rate of change of TFP of 1.9% per annum from 1972 to 1987, indicating quite good progress in a period after HYVs had already been widely adopted. However, decomposing the sources of change in TFP indicates that the most rapid progress in improving productivity has been made through labor-saving technology--especially the substitution of tractor power for bullocks. The gains in productivity resulting from biochemical technology--release of newer varieties, increased fertilizer use, improved weed control, and the adoption of other management practices--appeared quite modest and may even have been negative until the mid-1980s (Figure 13).

Finally, an important issue in assessing sustainability of an agricultural system is its stability in the face of external shocks. In the wheat-based systems of Asia, the major biotic shock is likely to arrive in the form of a new race of one of the rust




Source: Sidhu and Byerlee (1990)

**Figure 13. Index of Total Factor Productivity in Wheat Production, Punjab.**

diseases. Farmers often replace varieties slowly, and a strong tendency for large areas of Asia to be sown with one or two dominant varieties has impeded varietal diversification (Table 1). This lack of diversification appears to be less of a plant breeding problem and more of an institutional problem created by ineffective seed systems and extension. Occasionally it has led to disease epidemics and substantial yield losses, as in Pakistan in 1978.

Given the high levels of fertilizer and tubewell water now used in most irrigated areas, the most likely economic shock would be a sharp increase in energy prices and hence fertilizer and water prices. While sharp price increases are possible in the short term, it is unlikely that a long term increase will be experienced until well into the next century (Chapman and Barker 1987).

The issue of whether the stability of grain yields has been improved or reduced in the wake of the Green Revolution has been extensively debated. In fact, contrary to the widely held belief that the seed-fertilizer technology increased instability in grain yields, the experience in India suggests that yield instability has actually decreased significantly since the Green Revolution. Singh and Byerlee (1990) calculate that the coefficient of variation in wheat yields in India declined from 17% in 1954-65 to 7% in 1976-86. This decrease was consistent across states and regions. Hence, the ability of major wheat-based systems to withstand external shocks, such as drought, may have improved over time.

Overall the evidence on changes in productivity in the irrigated wheat-based systems of South Asia is not conclusive. Worrying indications of declining productivity are apparent from results of some long term trials and from trends in various estimates of partial or total factor productivity. But decreased yield variability suggests that progress has been made in achieving more stable production systems.

**Emerging Sustainability Problems at the Macro-Level**

Another important element in assessing sustainability is to monitor changes in the quality of the resource base over time. A reasonable amount of information exists to evaluate two major sustainability problems in irrigated systems: groundwater exploitation and increased problems of salinity/waterlogging. Falling groundwater levels have become a major issue in irrigated wheat production in the dry areas of central and western India, and it seems that much of the Indian Punjab has reached the maximum sustainable level of groundwater use (Chopra 1990). Overexploitation of groundwater is encouraged by the spread of electrification, high subsidies on electricity, flat rate payments for electricity per crop season, and lack of control on the installation of new tubewells.

Less is known about pollution of groundwater by agricultural chemicals, but given that high rates of nitrogen are used in many intensively cropped systems of Asia, nitrate contamination of groundwater is expected to be an increasing problem. Farmers in Ludhiana District in the Indian Punjab now apply over 300 kg/ha of nitrogen to the dominant rice-wheat cropping pattern--over double the annual rate of nitrogen application to maize in the USA. Not surprisingly at least one study shows a substantial increase in nitrate contamination of groundwater in the Indian Punjab since the mid-1970s (Singh et al. 1987).

A review of major salinity and waterlogging problems is beyond the scope of this paper. Some areas, such as the Indian Punjab, have made great progress in reducing the problem (Chopra 1990). In other areas, such as Rajasthan, the problem has worsened. But while the threat of salinization in major irrigation systems remains a serious issue, the significant investments made in draining and reclaiming saline land in recent years seem to be paying off in India and Pakistan.

**Emerging Sustainability Issues at the Micro-Level**

Several potential sustainability problems have been identified at the farm or micro-level. Because these problems often involve much more gradual changes over time and are soil- or pest-related, they are often much less visible than large-scale problems, such as groundwater depletion, and are difficult to observe and measure over time. Most of these problems arise from the intensification of input use and greater intensification and specialization of cropping systems.

1) Nutrient depletion or mining. Perhaps the most common sustainability problem occurs because nutrients are extracted from the soil (because of increased cropping intensity and yields) at a rate higher than they are added, especially given the fact that crop and animal residues are increasingly used for non-farm purposes. In some cases nutrient depletion involves macronutrients (nitrogen, phosphorus, and potassium) and sometimes secondary and micronutrients such as sulfur, zinc, and boron. In long term trials, yield declines may be observed even at the recommended level of fertilizer. In farmers' fields, lower doses of fertilizer and unbalanced mixes of nutrients may lead to even more of a problem of nutrient mining (Table 4).

**Table 4. Nutrient balance for rice-wheat-rice rotation in Northwest Bangladesh[a]**

| | Nutrients applied | Nutrient export | Difference |
|---|---|---|---|
| | | (kg/ha) | |
| N | 138 | 164 | - 26 |
| $P_2O_5$ | 116 | 78 | 38 |
| $K_2O$ | 57 | 222 | -165 |

Source: Saunders (1990).

[a] total grain yield of 8.1 t/ha/year.

2) Declining soil organic matter. The decline in use of organic manures and the general pattern of removing all crop residues is probably reducing soil organic matter content, as observed in several long term trials (IARI 1989). This change in practices has implications for nutrient availability, nitrogen efficiency, and soil physical properties.

3) Other soil-related problems. Various other factors may gradually increase certain soil problems which are difficult to detect in the short term without careful measurement. For example, the use of poor quality groundwater in Pakistan and India has exacerbated sodicity problems (Byerlee and Siddiq 1990; Bajwa and Josan 1989). Excessive tillage and inappropriate tillage instruments have increased soil compaction. Other soil physical properties may have deteriorated as well, especially in the rice-wheat system.

4) Pest-related problems. As noted earlier, specialized cropping patterns such as continuous rice-wheat rotations may increase the incidence of pests. The most obvious example is the spread of Phalaris minor in wheat in much of the rice-wheat system. Soil health problems in these systems may also be more serious than currently believed, as indicated by yield increases of 10-20% in experiments on rice-wheat rotations in Nepal when soils are pasteurized to kill microorganisms (Dubin and Bimb, pers. com.).

This brief review of micro-level sustainability problems suggests that many problems, such as nutrient mining, should be easily resolved in the short term by technical solutions. More intractable problems, such as declining soil organic matter, might also be arrested; it is estimated that 200,000 ha in the Indian Punjab is now sown annually to green manure crops.

But by far the most important limitation to understanding and solving these sustainability problems is the lack of information to make accurate assessments of the long term changes in the quality of the resource base. To identify emerging sustainability issues more precisely and take appropriate remedial action, there is an urgent need to allocate resources to monitor trends in the use of inputs and other management practices, soil physical and chemical properties, groundwater quality, and pest populations in major cropping systems of South Asia.[9] The investment required for monitoring is modest in relation to the potential implications of these problems to the hundreds of millions of people depending on continued productivity increases in irrigated agriculture in South Asia.

9 CIMMYT and IRRI have initiated one such effort, in collaboration with national research systems of South Asia, to diagnose sustainability problems and monitor changes in the resource base in the important rice-wheat systems.

## Institutional and Policy Issues

Progress along the continuum of technical change in Asia, from the technological breakthrough to input intensification and on to input efficiency, requires that institutions and policies evolve to serve the changing needs of the food grain sector at each stage of technical change. The response of institutions and policies to technical change in the past, and the ways that they will have to meet the demands of the future, especially the emerging sustainability issues, are discussed here with respect to the research system and technology and information transfer.

### The Research System

The rice and wheat revolutions originated with the use of improved varieties, which were largely an imported technology. The spectacular success of this technology in Asia stimulated the development of strong national plant breeding programs for major food grain crops. These programs have matured over time to release newer, even higher yielding varieties resistant to diseases, and to develop more locally adapted varieties that fit specific agroecological niches and cropping patterns.

The strength of plant breeding research in Asia contrasts with the relative weakness of crop and resource management research (CMR), a term used in this paper to refer to almost all non-genetic research (that is, research on tillage, fertilization, pest control, irrigation scheduling, planting date and establishment, etc.). In the input intensification stage, which depends on increasing numbers and levels of inputs, research has played a minor role relative to improved input distribution. Indeed, in irrigated wheat production, it is often difficult to identify which of the management practices used by farmers can be directly attributed to the results of CMR (Traxler 1990).

The successful transition from the input intensification to input efficiency and maintenance of the resource base will require much improved information on crop and resource management for specific sites. Most of this information will need to be provided by CMR programs, which must become more decentralized and focus on the agroecological and socioeconomic circumstances of farmers at specific locations. CMR recommendations will have to evolve beyond the current "recipe" approach, which emphasizes the quantities of inputs to be used for large heterogeneous areas. For example, despite the thousands of fertilizer experiments that have been conducted in the past two decades throughout India and Pakistan, practically the same fertilizer recommendation is given for irrigated wheat. If farmers are to enter the input efficiency stage, they will need a wider range of technical information enabling them to grasp the scientific basis of the new technology and better adapt the technology to their own needs.

In addition, to address the emerging sustainability issues reviewed in this paper, CMR must adopt a longer term approach combining 1) strategic research focusing on critical issues for major crop rotations (e.g., declining organic matter or late planting and poor stand establishment in the rice-wheat rotation); 2) monitoring the resource base at the farm level; and 3) adaptive research to tailor "sustainable" practices (e.g. reduced tillage, green manure crops, etc.) to local conditions.

A major challenge to research on sustainability problems is to evolve institutional mechanisms that promote an integrative, problem-solving approach to research that brings together a broad range of disciplines in the physical, biological, and social sciences. Increased intensity and specialization in cropping systems will also require commodity research programs to coordinate their work and communicate more effectively. This is particularly true for rice and wheat research programs, because of the importance of the two crops in major cropping systems. Most research systems in South Asia are presently too compartmentalized to meet the needs of research on the complex problems emerging in many intensive irrigated systems.

**Technology Transfer: Institutions and Policies**

The activities of the public sector were crucial to initiating the Green Revolution, for the public sector played the chief role in releasing seed of the new varieties and in providing complementary inputs--especially fertilizer and water. The public sector also made a substantial investment in rural infrastructure, roads, and irrigation systems, which were important to the continued success of the Green Revolution. With the input intensification stage came a major shift from public-to-private sector distribution of inputs. This shift was facilitated by the increasing volume of inputs (especially fertilizer) being used and continuing improvements in infrastructure. Nonetheless, governments have often carefully controlled prices charged by private sector distributors.

In the input efficiency stage, improvements in information and skills play a much larger role than increased use of inputs in improving productivity. As mentioned earlier, farm-level studies in the 1980s on rice and wheat suggest that, in post-Green Revolution areas of Asia, technical inefficiency may average around 30% (Ali and Byerlee, forthcoming). Moreover, the variables that consistently explain this variation relate to farmers' knowledge and skills (e.g., extension contact, technical knowledge scores, and education). The increasing emphasis on "sustainable practices," most of which are quite complex and require considerable information to manage well, will further increase the need for improved information and skills.

Efforts in the 1980s to upgrade extension systems in part reflect institutional efforts to meet this new stage of technical change. For example, the T & V extension system promoted by the World Bank is now widely used in Asia. Although it has met with some successes (Feder et al. 1987), this system remains directed toward "input promotion" rather than "input efficiency." In addition, extension is limited by continued poor contact between research and extension, the failure of CMR to provide appropriate information, and reliance on the "recipe" approach to delivering extension messages that emphasize technological packages. Complicating the difficulties of transferring information to farmers is the fact that levels of formal education are low, especially in much of South Asia, which may increasingly limit farmers' capacity to efficiently use more complex technologies. Thus institutional change in extension, private sector information transfer, and rural schooling have failed to keep pace with farmers' needs for better technical information that can substitute for input use and accelerate the transition to the input efficiency phase of post-Green Revolution agriculture.

Two features of the price policy environment over the past two decades promoted the intensification of input use in South Asia. First, incentives for input use have been provided through subsidies, especially for fertilizer, but also for irrigation water and credit. Second, producer prices of major food grains, such as wheat, have been fixed through government price controls and restrictions on internal movement and importation of grain. While the appropriate level of procurement prices is open to debate, there is little doubt that government intervention has stabilized output prices and reduced the price risk to farmers in using purchased inputs. In the late 1980s both these policies are under review with a trend toward eliminating input subsidies and freeing producer prices. The removal of input subsidies is likely to accelerate the transition from input intensification to a stage that emphasizes more input efficiency. However, without a corresponding change in producer prices, which tend to be well below import parity prices, removal of input subsidies may result in a decline in production.

## Conclusions

Over the past 25 years, food grains in Asia have experienced extraordinarily rapid and broad-based gains in productivity. The pace of change has been especially high in wheat, both in areas where wheat is the staple food (northwestern India, Pakistan and northern China) and areas where it is a secondary crop, usually grown after rice (for example, in northeastern India and Bangladesh). Over this same period, new agricultural land has essentially been exhausted in Asia, except in southeast Asia. The area increases that were important in the growth in cereal production up to the 1960s can no longer be expected to contribute to increased food production. Indeed in many densely populated areas, yield increases will need to compensate for a decline in area sown to cereals. In the 1980s, the growth rate of yields has also slowed, moving to a level only slightly exceeding the population growth rate.

The rapid gains in wheat productivity in the 1960s and 1970s were stimulated by the widespread adoption of HYVs and fertilizer and improvement in irrigation water supplies. In the 1980s, growth was largely due to more intensive and balanced use of fertilizer and in some cases adoption of chemical weed control, seed treatment, and other improved practices. In many areas the returns to further intensification of input use are diminishing rapidly, and further gains in productivity will come largely through using inputs more efficiently. Nonetheless, for large areas, especially in India, a significant and economically recoverable yield gap still exists. The increase in wheat production that would result from closing the yield gap should be sufficient to meet the demand for wheat in the next decade or so. This can be done by using higher levels of inputs (especially fertilizer), but productivity gains will increasingly depend on the adoption of better cultural practices which enhance input efficiency, such as improved plant stand establishment, balanced fertilizer doses, and better weed control. Closing the yield gap thus requires a somewhat different research strategy, will be the sum of many small incremental changes in productivity, and will be more difficult to organize and manage.

A major uncertainty is whether current levels of productivity can be sustained, especially in light of the increasing intensification and specialization in cropping systems in many areas. At this stage the evidence for sustainability problems is mixed. There appear to be problems in the exhaustive rice-wheat system in many areas, especially in maintaining rice yields, and problems also seem to be emerging in large wheat-growing areas such as the Punjab of Pakistan. Although discussions of sustainability often emphasize large-scale problems such as groundwater depletion, salinization, etc., the evidence presented here suggests that more attention should be given to the micro-level problems of long term changes in soil fertility, physical and chemical properties, soil diseases, and weed populations. These changes, which are often difficult to measure and track over time, deserve far more attention. Research to assess the current status of these variables and to monitor changes over time is urgently needed since the cost of solutions is likely to increase as these problems worsen.

Realizing future gains in productivity in Asia will also require important changes in the institutions serving agriculture. Research systems need to adjust to a new stage of technical progress in which information will substitute for inputs to enhance efficiency and sustainability. In particular, research must adopt a more integrative and longer term approach to crop and resource management that promotes multidisciplinary and multicommodity collaboration in diagnosing and solving problems in major cropping systems. Likewise, the technology transfer system will need to give more attention to providing information and skills to farmers confronted with managing an increasingly complex agriculture. The growing interest in managerially complex "sustainable" practices, such as integrated pest management, only increases the urgency for developing appropriate institutions that can support the transition to the next stage of post-Green Revolution development in Asia.

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