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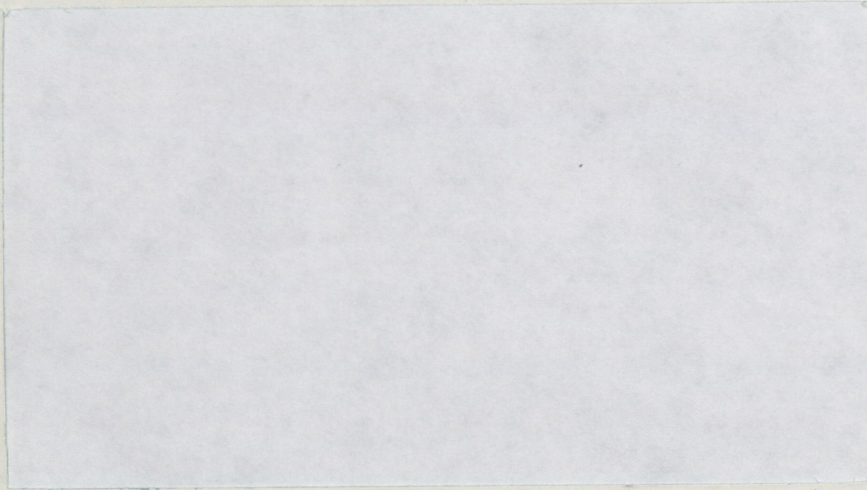
**Technical Change, Productivity, and
Sustainability in Irrigated Cropping Systems of
South Asia: Emerging Issues in the
Post-Green Revolution Era**

Derek Byerlee*

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* Views expressed in this paper are those of the author and do not necessarily reflect CIMMYT policy. The author appreciates the help of many colleagues in CIMMYT and national research systems who have provided information and comments during the writing of this paper.

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Abstract

Recent trends in South Asia's irrigated cropping systems are analyzed, giving particular attention to systems in which wheat is an important crop. Much of the recent success in increasing food production in South Asia is due to success in wheat production. The paper presents an overview of the stages of technical and institutional changes in South Asian agriculture from the pre-Green Revolution era through to the current post-Green Revolution stage. The paper then identifies emerging problems, both technical and institutional, which will impinge on the ability to maintain gains in food grain productivity and sustain the resource base over the next 10-20 years. A new strategy is proposed to ensure productivity increases in South 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.

Introduction

Over the past three decades since the advent of the Green Revolution, food grain production has grown at an unprecedented rate in Asia compared to other regions and compared to historical growth rates. However, this rapid growth appears to be ending. In the 1980s cereal production grew more slowly than in any of the three preceding decades, primarily because of the radically diminished growth in area sown to cereal crops (Figure 1). The contribution of expanding area has declined in every decade since the 1950s, when increases in the area sown to cereal crops accounted for about half of the growth in cereal production. By the 1980s, growth in the area sown to cereals had stagnated.

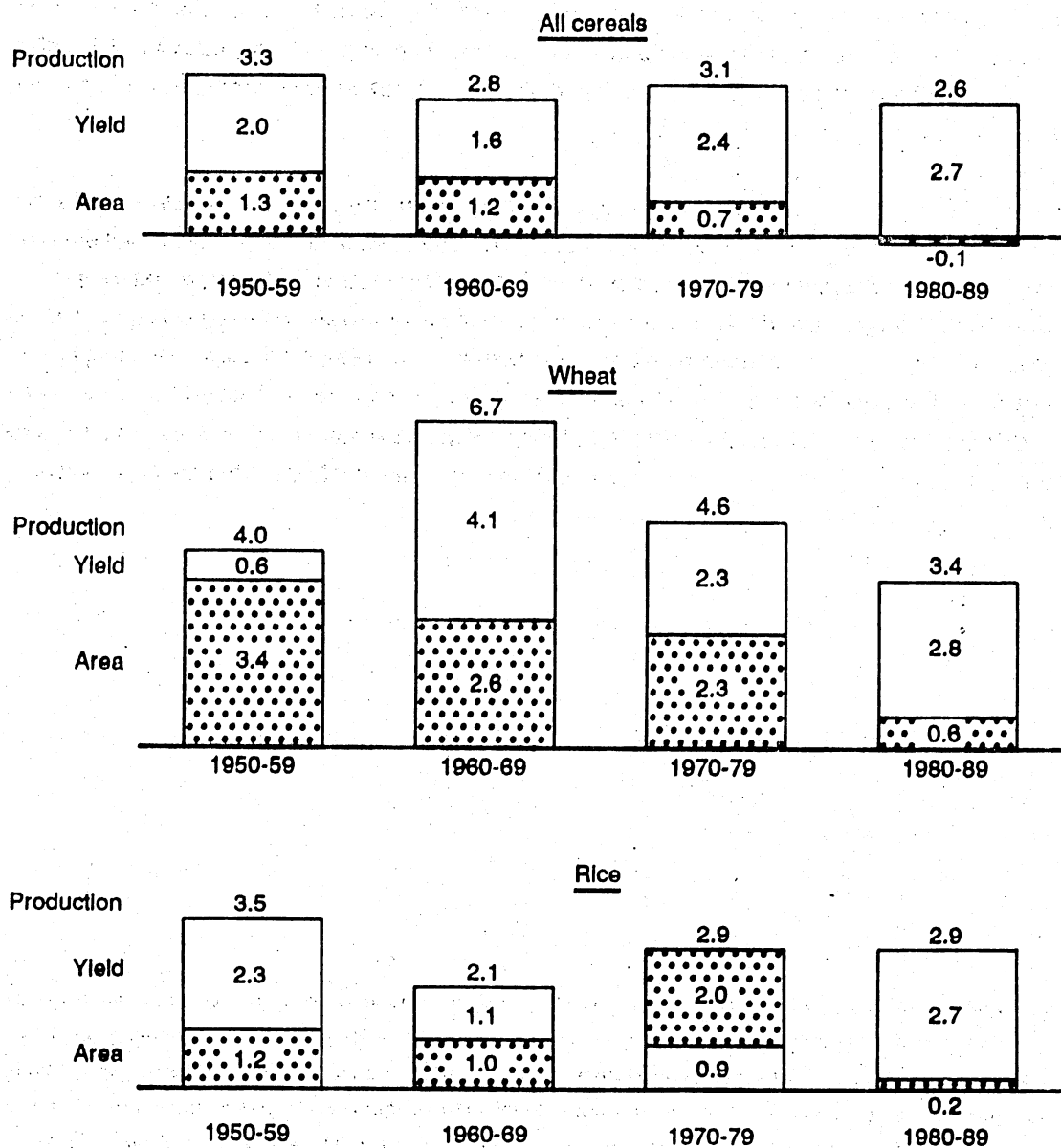


Figure 1. Average annual growth rates (%/yr) in area, yield, and production of cereal crops in South Asia over four decades.

These trends have two important implications in projecting future food production in South 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.) Second, yields of cereal crops in South Asia have risen at an unusually high rate in the past 25 years because the "easy gains" from the adoption of high yielding varieties and fertilizer have been obtained. More modest progress must be expected in the future. The effects of these trends will be lessened partly by slower growth in demand for food grains, but demand will nevertheless grow at 3% annually in the 1990s. This demand must be met entirely by increasing yield per unit area or by increasing imports (CIMMYT 1989).

Slower growth in food grain production has two other important implications for South Asian countries. First, increased productivity in basic food grains is a key factor in alleviating poverty, both because cereal production is often seen as an "engine" for stimulating labor intensive growth and because food prices are an important determinant of the welfare of the poor (Mellor 1990). Alleviating poverty must remain a central aim of development in South Asia, where over 500 million people--half the world's poor--live (World Bank 1990). Second, the sustainability of South Asia's increasingly intensive cropping systems is being questioned. If slackening growth in food production reflects a deterioration of the resource base in irrigated agriculture, the implications for future generations, when population pressure on the land will be even greater, are serious indeed.

These and other recent trends in South Asia's irrigated cropping systems are interpreted in the pages that follow. Because much of the recent success in increasing food production in South Asia is due to success in wheat production, particular attention is given to systems in which wheat is an important crop--that is, the large and densely populated areas of the Indo-Gangetic plains of Pakistan and northern India, the *terai* (lowlands) of Nepal, and parts of Bangladesh.¹ This paper focuses on emerging problems, both technical and institutional, which will impinge on the ability to maintain gains in food grain productivity and sustain the resource base over the next 10-20 years. A new strategy is proposed to ensure productivity increases in South 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.

¹ Wheat is the second major food grain in South Asia, after rice. Over 80% of the wheat in South Asia is grown under irrigation or in areas receiving adequate rainfall moisture. Wheat is the principal food crop in the irrigated cropping systems of the Indo-Gangetic plain, extending from Pakistan through to western Uttar Pradesh in India. In other locations, including Bangladesh and northeastern India, wheat is often grown in the short cool season after rice (the chief staple food). During the past 25 years in South Asia, wheat production rose by the extraordinarily high rate of nearly 6% annually, but recent signs of sharply slower growth in wheat production have appeared (Figure 1).

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 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:²

- Phase 1:** The pre-Green Revolution phase, when gains in productivity per unit of land area were modest. Expansion in area planted to food grains, especially irrigated area, played the crucial role in increasing food production.
- Phase 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 3:** The first post-Green Revolution phase, beginning after the widespread adoption of HYVs, when *intensification* of input use, especially chemical fertilizer, substituted for increasingly scarce land for agriculture.
- Phase 4:** The second 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, evolves to allow improved managerial and information skills to substitute for input use and increase input *efficiency*.

Figure 2 depicts these phases in the conventional 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. However, for various reasons, farmers are unable to exploit the full benefits of the new technology immediately and operate at B below the technological frontier, MV_2 .

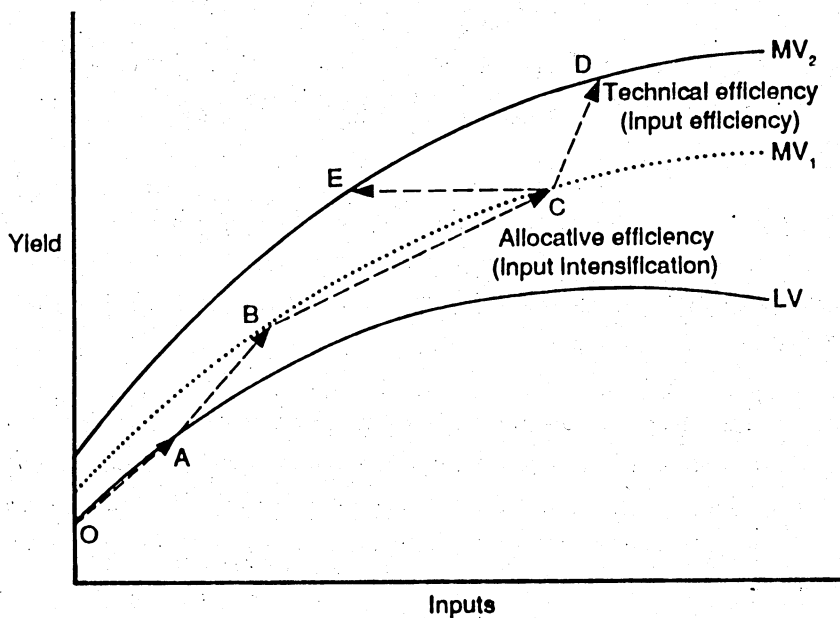
In Phase 2, when input use intensifies, farmers move along the new production function by using higher levels of complementary inputs. This phase may be viewed as a time of improving *allocative efficiency* as the marginal value of productivity of each input approaches its acquisition price. Finally, as farmers approach allocative efficiency, they

² In practice these stages often overlap.

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 phase in the process of technical change identified above 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 the technology is adopted, strong local crop breeding programs are required 1) to maintain the gains that have already been made, especially where resistance to pests and diseases of the new varieties breaks down (Pray and Ruttan 1990), and 2) to 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 rising levels of input use.



OA	Phase 1	Expansion of land area	
AB	Phase 2	Land saving technical breakthrough	
BC	Phase 3	Input Intensification	
CD	Phase 4	Input efficiency	} Post-Green Revolution
CE			

Figure 2. Simplified view of stages of changes in productivity in land intensive agriculture.

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 requires considerable information and skills to execute successfully.) At the same time, in this phase of technical change the institutions responsible for disseminating information, such as extension services, 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 subsidized input prices. These policies aim to provide incentives for using inputs more intensively and overcoming market imperfections arising from perceived risk, scarce capital, poor infrastructure, and the costs of learning to use the new technology. Removing these subsidies in the later stages of technological evolution gives producers one incentive for using inputs more efficiently and possibly moving from C toward E in Figure 2.

Sustainability

Technical and institutional changes that increase productivity must also ensure the sustainability of agricultural production systems. The term "sustainability" has been given varied interpretations. This paper uses a definition adapted from Lynam and Herdt (1988) and CIMMYT (1989): sustainability is the ability to achieve stable gains in productivity over the long term while maintaining or even enhancing the quality of the agricultural resource base. Continued productivity increases are clearly one critical element of a sustainable agriculture.

Problems of maintaining the quality of the resource base can be divided into two categories, depending on their ease of solution over time. Some problems are more 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 the removal of subsidies on energy prices.

Sustainability problems also differ depending on the cost of their solutions. 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*, as in the case of 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 (for instance, a sharp rise in the price of a key input such as fertilizer) or changes 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 irrigated cropping systems of South Asia over the past three decades have followed the phases 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 input use suggests that more intensive use of inputs will make a smaller contribution to production increases in the future.

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

	Pakistan (Sheikhapura/ Gujranwala, Punjab, 1990)	India (Ludhiana, Punjab, 1988)	Bangladesh (Dinajpur, 1990)
Percentage 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
Percentage area planted to dominant variety	59	67	51
Average fertilizer applied (kg/ha)			
Nitrogen	82	138	72
Phosphorus	49	74	25
Potassium	0	4	25
Total	131	216	122
Percentage apply herbicide	35	65	0
Average yield (t/ha)	2.4	3.9	2.7

Source: Data for Pakistan from the Agricultural Economics Research Unit, Faisalabad (pers. comm.); for India, from the Punjab Agricultural University (pers. comm.); and for Bangladesh, from Saunders (1990).

a Measured in years from varietal release.

b Data are for previous year(s).

na = not available.

High Yielding Varieties

The rapid diffusion of modern-semidwarf wheat and rice varieties (that is, HYVs) in South Asia is well documented (see Dalrymple 1986a, 1986b). Two aspects of the diffusion process are important for the purposes of this paper. First, the use of HYVs expanded particularly rapidly in the irrigated areas of South Asia, and the adoption process was essentially completed by the late 1970s (Figure 3). During the 1980s, only minor gains have been made by the substitution of HYVs for local varieties.

A second important feature of the diffusion of HYVs in South 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 throughout South Asia have steadily improved the genetic yield potential of newer wheat varieties by 0.5-1.0% per year (Byerlee 1990; Waddington et al. 1986). Although adoption of newer varieties often has been slow (Halsey 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 modest to high returns to investments in wheat breeding (although lower than the returns to the original development of HYVs) (Byerlee 1990). In rice, by contrast, very limited progress has been made in improving yield potential (Khush 1990).

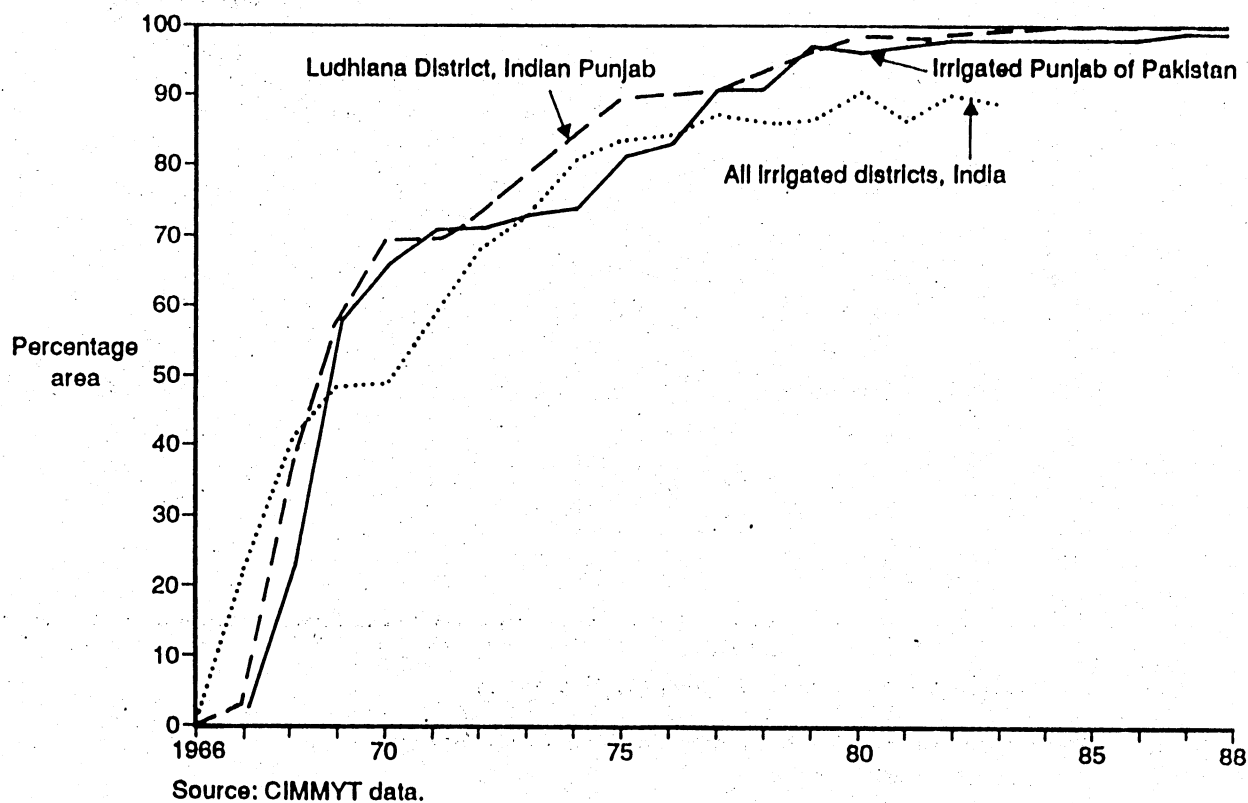


Figure 3. Percentage area sown to semidwarf wheat varieties in irrigated areas of India and Pakistan.

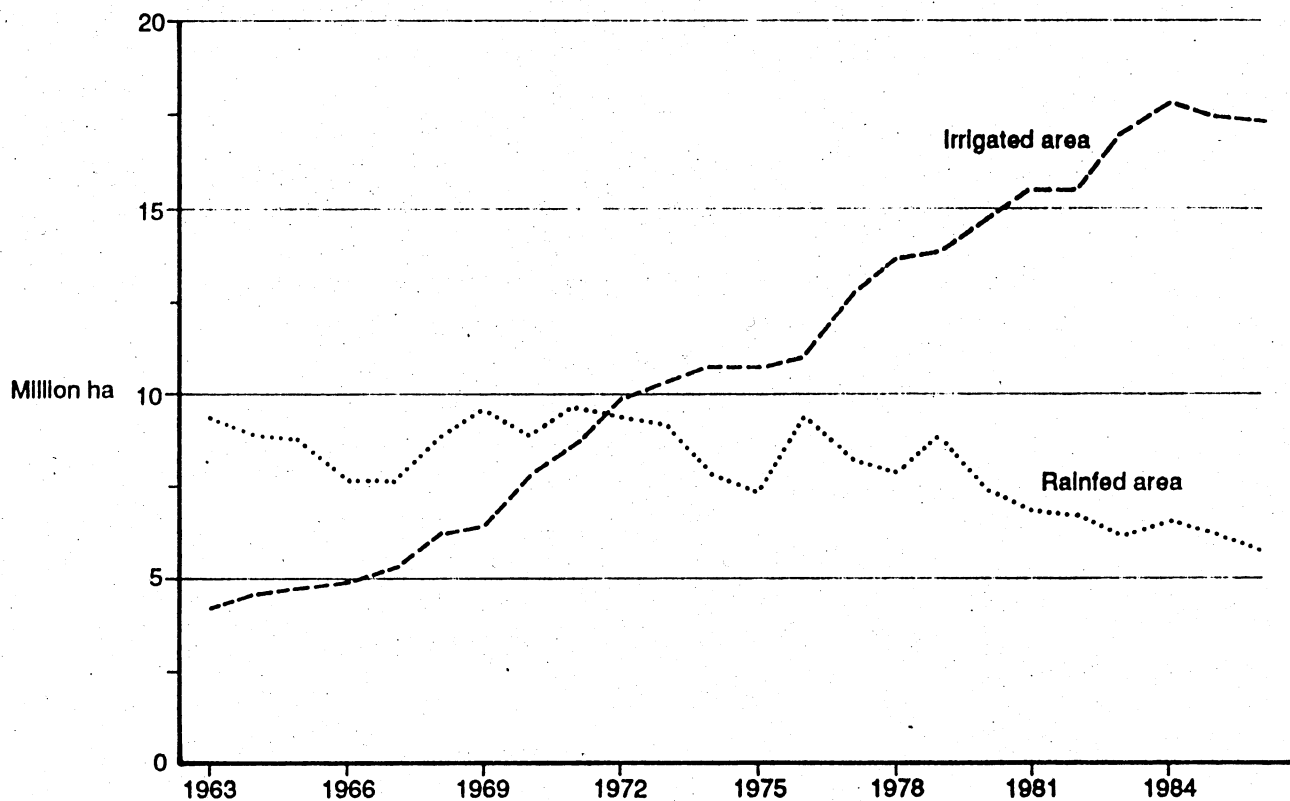
Irrigation

More abundant supplies of irrigation water contributed greatly to increasing cereal area and yields in the 1960s and 1970s in much of South Asia. For example, in India the percentage of irrigated wheat area grew from 33% in 1961 to 75% in 1988 as irrigation facilities became available on formerly rainfed land (Figure 4) and as wheat substituted for other crops on irrigated land. Irrigation alone may explain at least one-third of the increase in Indian wheat production over this period (Ahluwalia 1989). However, by the 1980s, when irrigation facilities had been developed on the less expensive and less difficult sites, the expansion of irrigated area slowed (Table 2). Rapid installation of tubewells has also meant that groundwater accounts for an increasing share of the total irrigation water supply.

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

Period	Growth In irrigated area (%/yr)
1965-69	2.7
1970-74	1.9
1975-79	2.2
1980-84	1.0
1965-84	2.1

Source: Levine et al. (1988).



Source: *Fertilizer Statistics of India* (various issues).

Figure 4. Trends in rainfed and irrigated wheat area in India, 1963-86.

Fertilizer

Although 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 5). Only in the most advanced areas, such as the Indian Punjab, is fertilizer use on wheat levelling off around the recommended level of 200 kg of nutrients per hectare (Figure 5). 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 Punjab of India and Pakistan (Grewal and Rangl 1983; Aslam et al. 1989).³

The expansion in fertilizer use was achieved in three ways: by increasing the area fertilized; by applying nutrients other than nitrogen (especially phosphorus and sometimes potassium); and by 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 indicate widespread use of potassium in some locations (e.g., Bangladesh in Table 1).

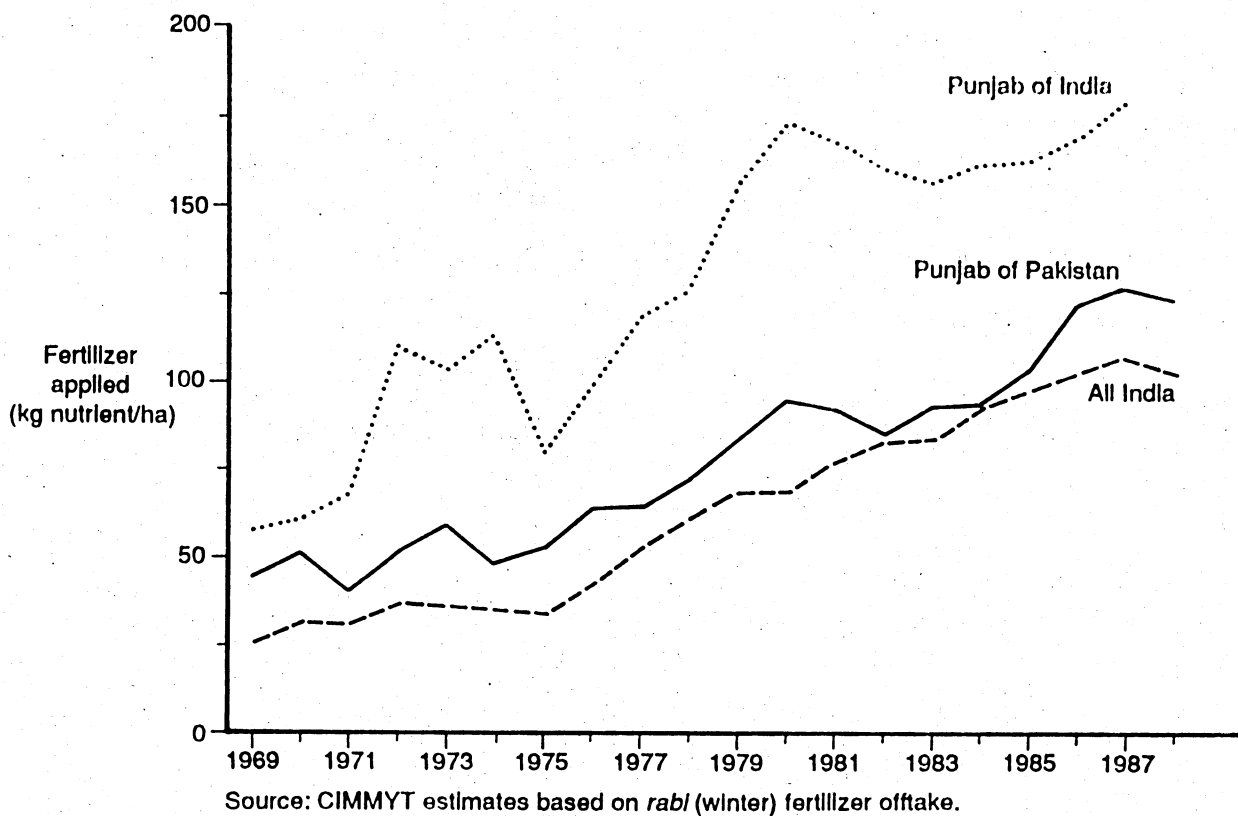


Figure 5. Estimated fertilizer use on wheat in South Asia.

³ The ratio of 5:1 is an average for all nutrients. Higher ratios are achievable for some nutrients, indicating the need for more balanced fertilizer doses.

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) and can be deduced from balance sheets for recycling organic manure and crop residues (Chopra 1990). For example, Sidhu and Byerlee (1990) find that the amount of organic manure applied by wheat farmers in the Indian Punjab has fallen by an average of 5% annually since 1972. 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 have increased.⁴

Pesticide Use

Contrary to popular opinion, the application of pesticides on new wheat varieties is minimal in most 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 some weeds from spreading swiftly and building up 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 quickly 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, and 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 (2.0-2.5 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 the Indian Punjab, however, the yield gap is relatively small and declining over

⁴ Even in China, which has a long history of heavy use of organic manure, application of manure is declining for similar reasons, and as chemical fertilizer becomes more readily available.

time (Figure 6). There is evidence that this gap has narrowed as variation in yields and input use has diminished among farmers, so that the difference between the lowest and highest yields in farmers' fields has also narrowed (Singh, Singh, and Bal 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 6). 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 yield gap is quite small.

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 1.0-1.5 t/ha (Aslam et al. 1989). Factors that can close the yield gap in the short term are timely planting (e.g., through zero tillage), better

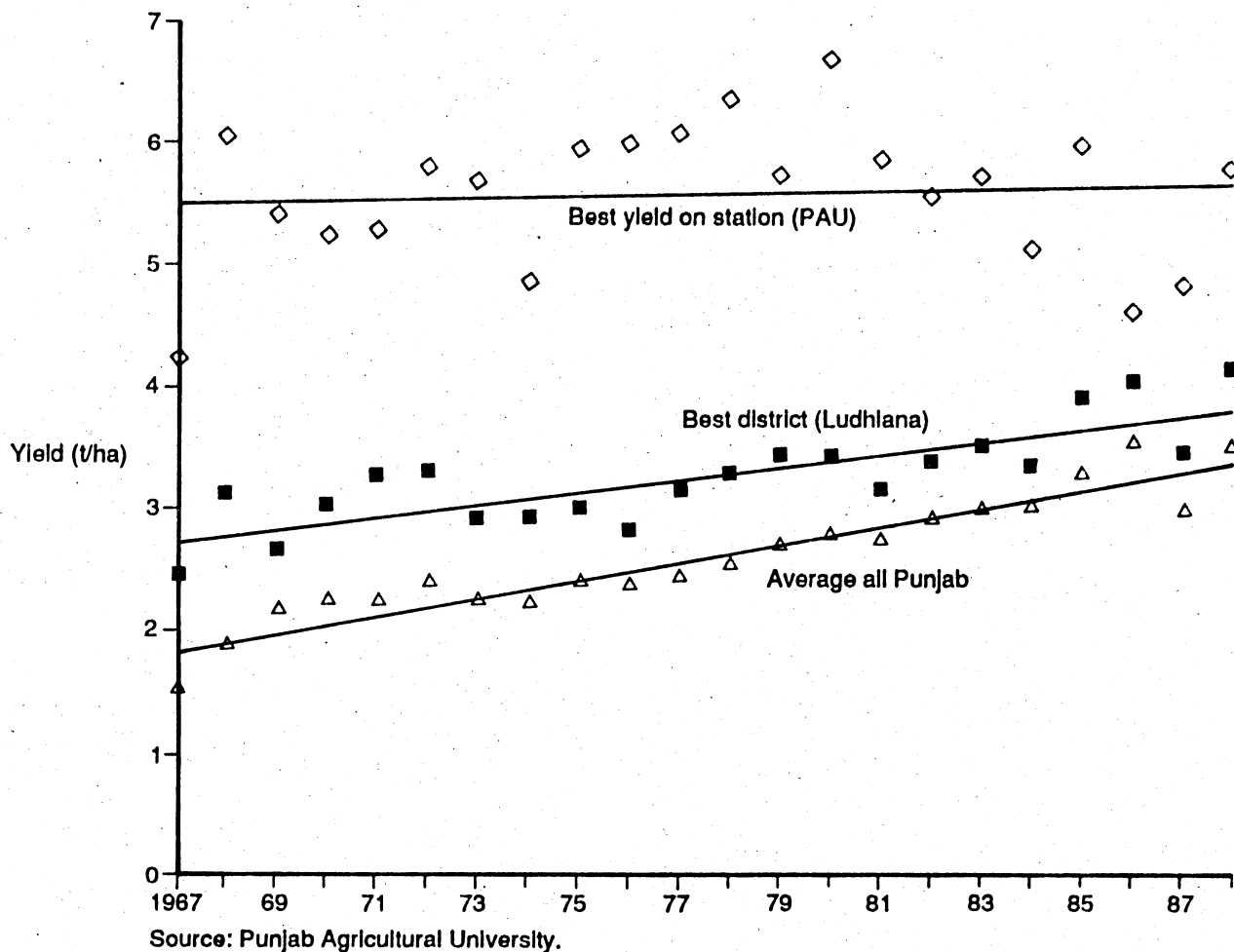


Figure 6. Farmers' yields and potential yield of wheat, Punjab, India.

plant stand, improved weed control, and fertilizer applications that are more balanced in terms of the mix of nutrients applied.⁵ 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.

The evidence presented above suggests that in much of South Asia's irrigated wheat-based systems, 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 recommended by researchers. Nonetheless, many of these areas have 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 1991, for a review). However, closing the technical efficiency gap will require important institutional changes that are discussed below.

⁵ It is likely that a yield gap of similar magnitude exists in irrigated wheat areas of northeastern India and Bangladesh, where yields are below 2 t/ha (Saunders 1990).

Increasing Intensity and Specialization of Cropping Systems

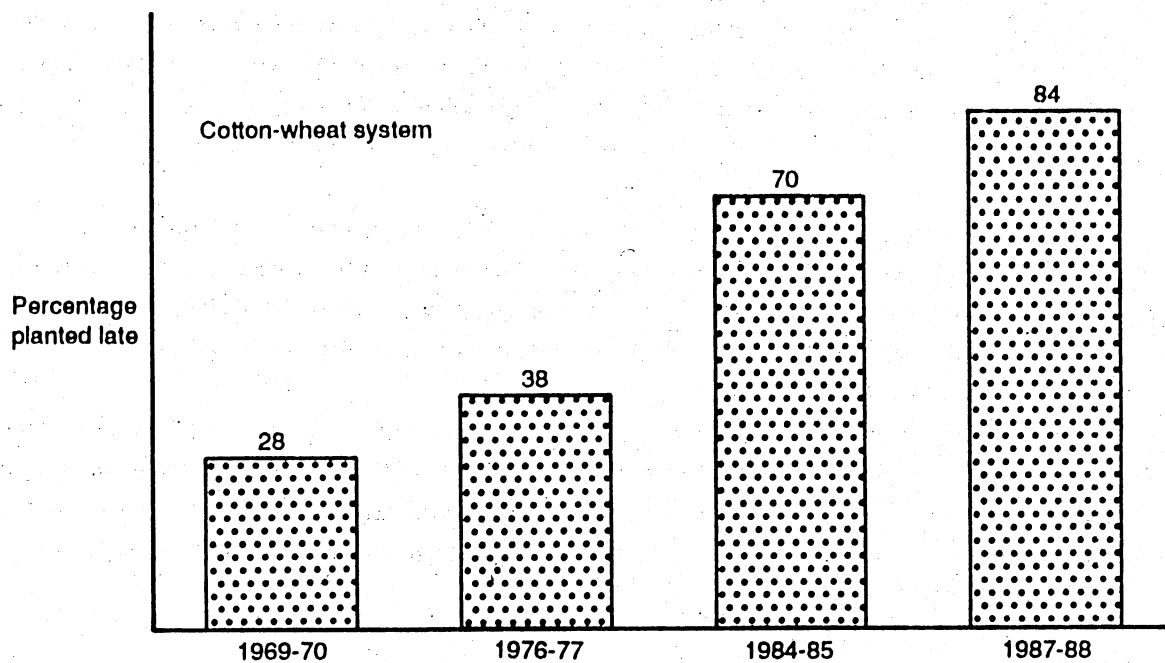
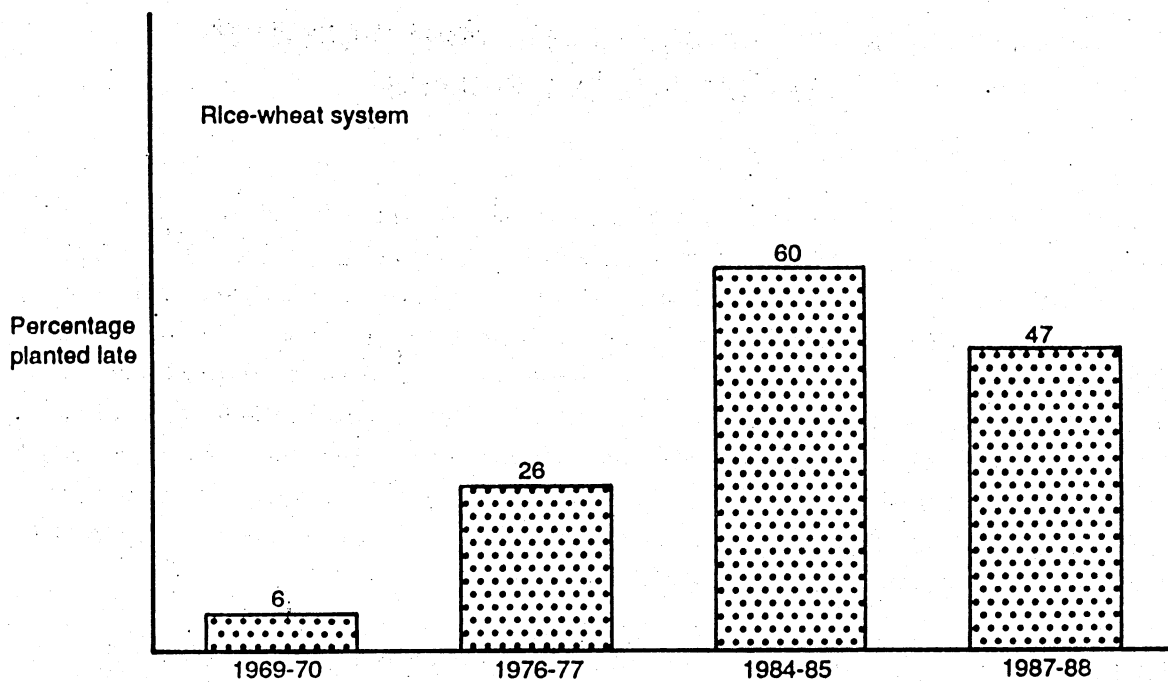
As input use has intensified in irrigated areas, a broad-based increase in cropping intensity at a steady 0.5-1.0% per year has also occurred. Cropping intensity in advanced areas of the Indian Punjab now approaches 200%. Crop intensification reflects growing land scarcity and has resulted from the adoption of HYVs (which mature earlier than the traditional varieties they replace) 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 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 (Hobbs, Hashmi, and Ahmed 1988).

In these newer rotations of wheat following rice, cotton, or soybeans, problems arising from conflicts in planting and harvesting dates have become acute. Wheat planting is commonly delayed across most of the irrigated wheat belt of South Asia. In India, where an estimated 40% of wheat is planted after the optimal period, the most serious delays occur in the rice-wheat areas (Tandon 1988). Survey data from Pakistan indicate a steady progression toward later planting in both major cropping systems--rice-wheat and cotton-wheat (Figure 7). 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 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 and 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 with the 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, Akhtar, and Hobbs 1987; Sharif et al. 1990). Breeders also screen for wheat varieties that perform well when planted late, and they are beginning to obtain positive results.

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 in fields planted continuously to rice and wheat for three or more years (the dominant rotation) show a significant negative tendency because of these problems (Byerlee et al. 1984).



Source: Byerlee and Siddiq (1990).

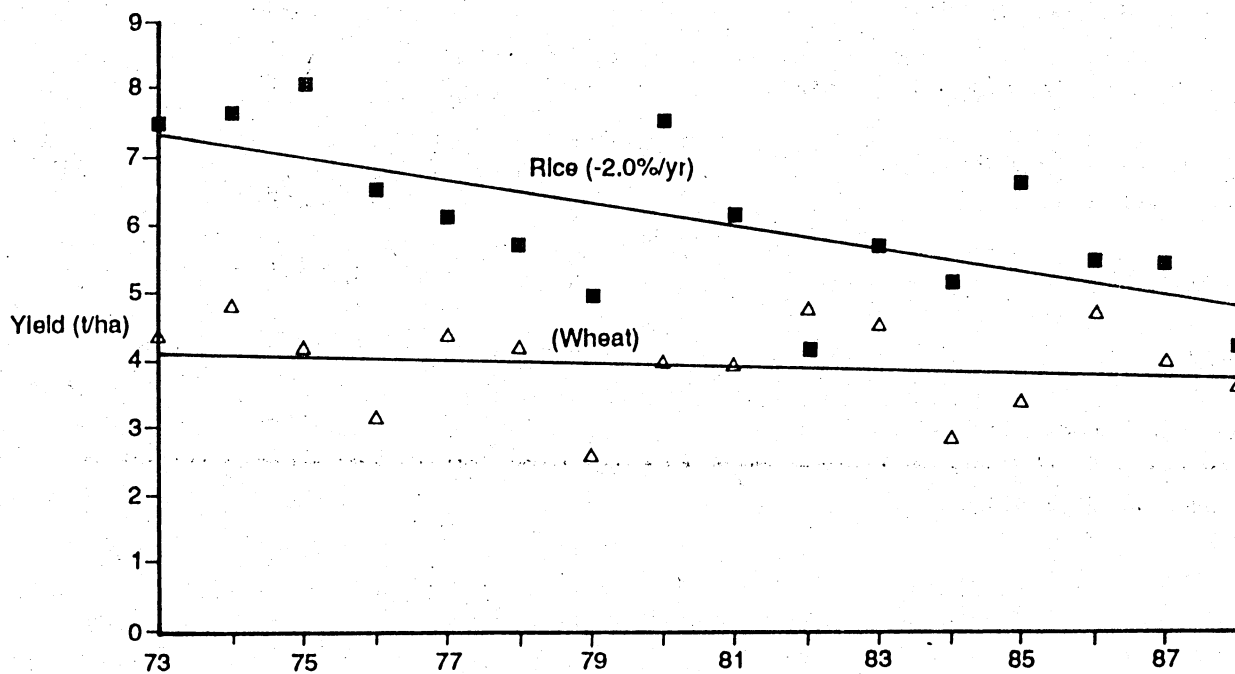
Figure 7. Percentage of wheat planted late (after 1 December), the Punjab, Pakistan.

Emerging Issues in Sustainability

Is There Evidence of a Sustainability Problem?

Any measure of sustainability should consider changes in productivity, changes in 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. In irrigated areas of South Asia, such a decline can be documented in only a few cases. A more meaningful measure of productivity is changes in total factor productivity (TFP). 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 determine 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 experiments conducted in India over about 15 years. The results of these trials indicate that a tendency for yields to decline 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 8--and Barrackpur in India, and Bhairahawa in Nepal (IARI 1989; P. Hobbs, pers. comm.). Declining yields are generally not evident in wheat (Figure 8) although, at 4 t/ha or less, wheat yields are low considering the high levels of inputs and management in these experiments. In addition, since newer wheat varieties were



Source: G.B. Pant University, Pantnagar.

Figure 8. Rice and wheat yields, long term trial, Pantnagar, India.

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.⁶ 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 sulphur 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 9).⁷

The most comprehensive approach is to measure the TFP over time, where sufficient data are available. For the Indian Punjab, Sidhu and Byerlee (1990) calculated an average rate of change of TFP of 1.9% per annum from 1972 to 1988, 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

Table 3. Projected and actual gains in wheat yields in the irrigated Punjab, 1972-86

Source of gain	Effect (kg/ha)
Switching from old to new varieties on remaining 33% of area still sown to old varieties	141
Genetic gains in yields of newer varieties (0.75%/yr)	138
Increased fertilizer use of 73 kg/ha at grain:nutrient ratio of 8.1	446
Total projected gain	725
Actual gain	375
Unexplained residual	-350

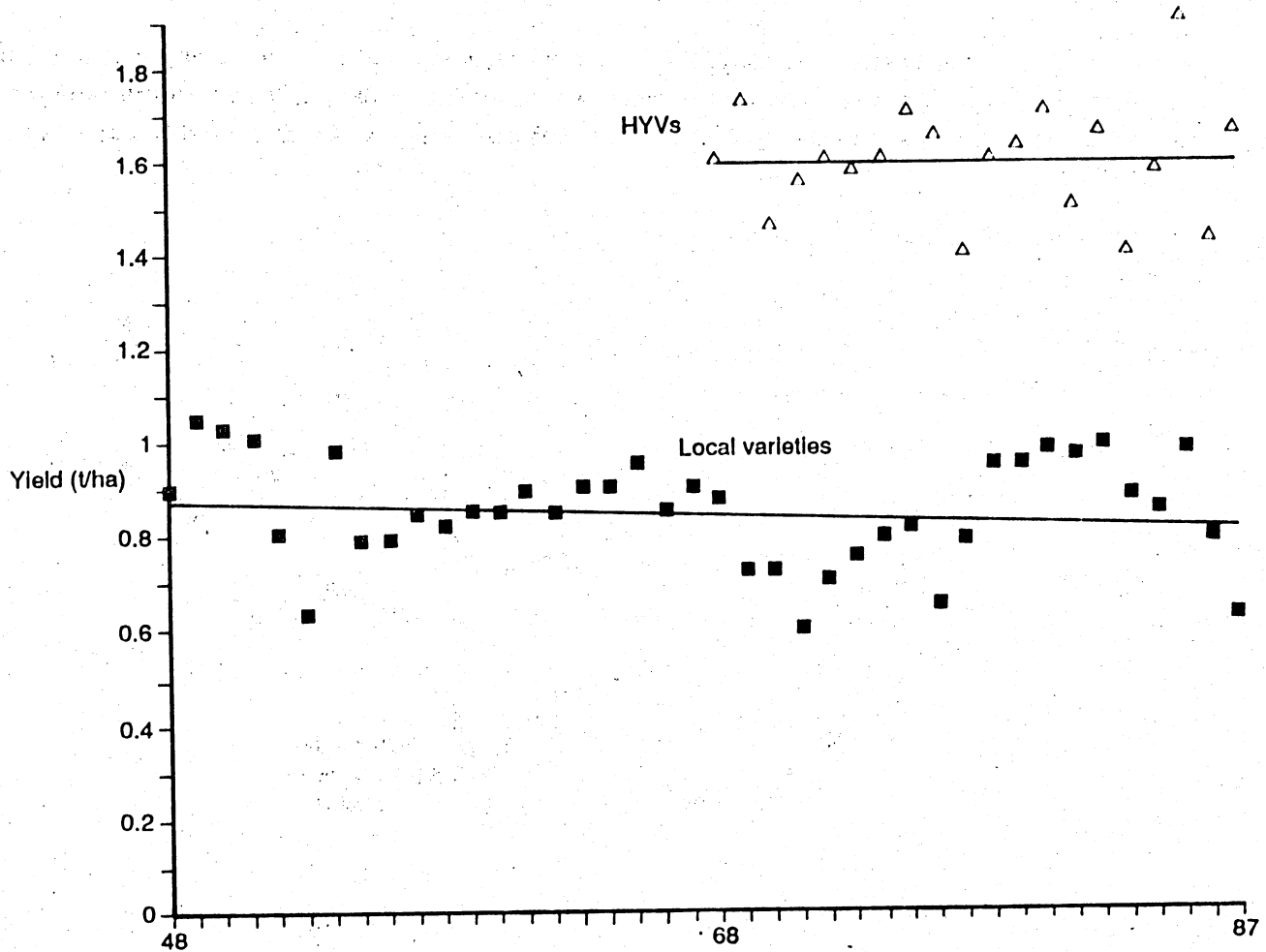
Source: Byerlee and Siddiq (1990).

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

7 However, overall average yields have risen with the continuing increase in the percentage of total area planted to HYVs.

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 improved cultural practices--appear to have been quite modest and may even have been negative until the mid-1980s (Figure 10).

Finally, an important issue in assessing the 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 diseases. Farmers often replace varieties slowly, and a strong tendency for large areas of South 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.



Source: Calculated from *Agricultural Statistics of Pakistan* (various issues).

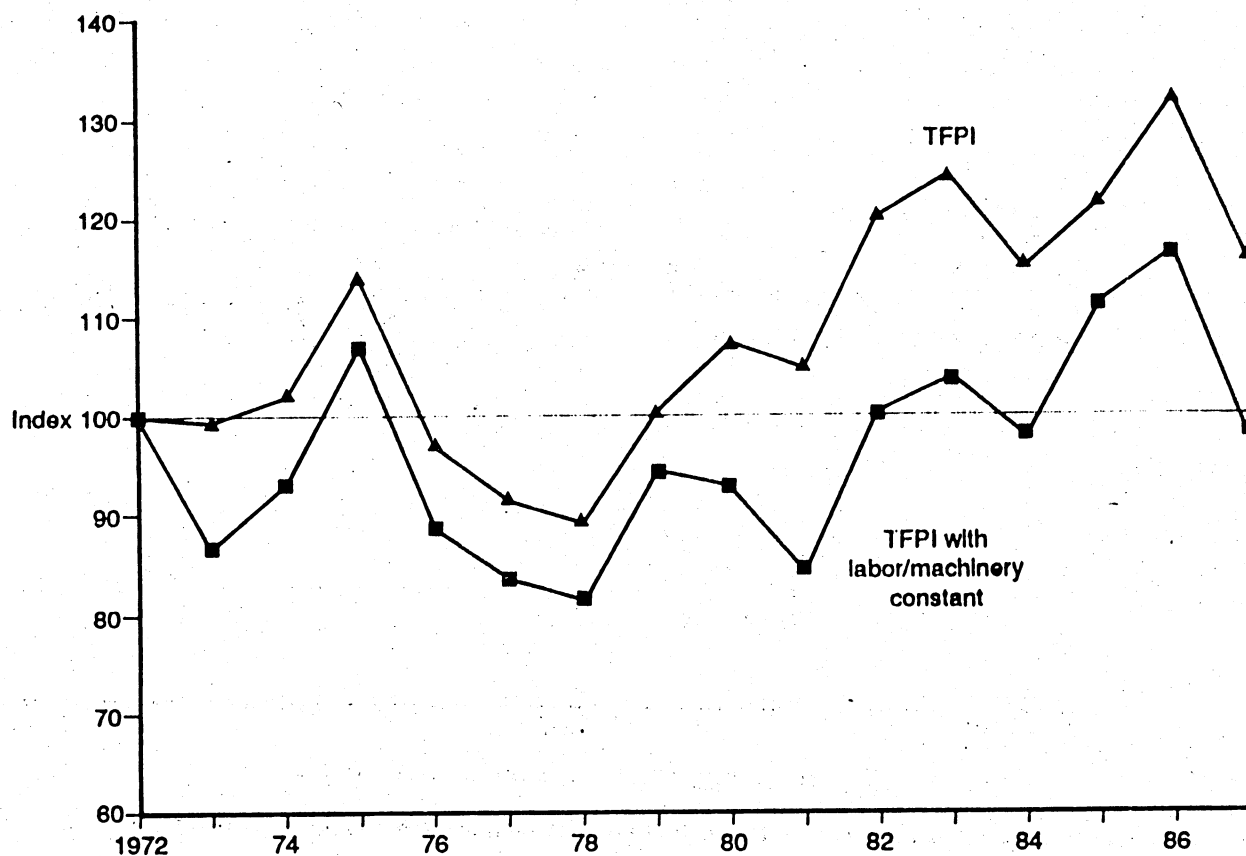
Figure 9. Trends in yields of local and high yielding wheat varieties, Punjab, Pakistan, 1948-87.

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 and irrigation status. 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 inconclusive. 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 salinity/waterlogging. Falling groundwater levels have become a major issue in irri-



Source: Sidhu and Byerlee (1990).

Figure 10. Index of total factor productivity (TFPI) in wheat production, the Punjab, India.

gated 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 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 Punjab and Haryana in India, have made significant 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 serious, significant investments in draining and reclaiming saline land in recent years seem to be paying off in India and Pakistan (e.g., Joshi and Parshad 1989).

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.

- **Nutrient depletion or mining.** Perhaps the most common sustainability problem occurs when nutrients are extracted from the soil (because of increased cropping intensity and higher yields) at a faster rate 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 when the recommended level of fertilizer is applied. 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).
- **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. For example, low soil organic matter may explain the low efficiency in utilization of nitrogenous fertilizer observed in many areas of South Asia (Desai and Ghandi 1989; Byerlee and Siddiq 1990; Abrol and Katyal 1990).

- **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 (Hobbs et al. 1988).
- **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 is 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. comm.).

This brief review of micro-level sustainability problems suggests that many problems, such as nutrient mining, can be 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 are now sown annually to green manure crops.

However, by far the most important limitation to understanding and solving these sustainability problems is the lack of information for making 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, and trends in soil physical and chemical properties, groundwater quality, and pest populations in major cropping systems of South Asia.⁸ 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.

Table 4. Nutrient balance for rice-wheat-rice rotation in northwestern Bangladesh

	Nutrient applied	Nutrient exported	Difference
	----- (kg/ha) -----		
N	138	164	-26
P ₂ O ₅	116	78	38
K ₂ O	57	222	-165

Source: Saunders (1990).

Note: Total grain yield of 8.1 t/ha/yr.

⁸ Together 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 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, are briefly discussed here with respect to the research system and technology and information transfer. In particular, the need for research and technology transfer institutions to develop new strategies to respond to the challenges of improving productivity and maintaining sustainability by increasing input efficiency will be highlighted.

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 South 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, and so forth). 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, it is often difficult to identify which of the management practices used by farmers (if any) can be directly attributed to the results of CMR (Traxler 1990).

The successful transition from 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. Recommendations derived from CMR will have to evolve beyond the current "recipe" approach, which emphasizes the quantities of inputs to be used and which takes little account of agroclimatic and socioeconomic differences among farmers. 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 all irrigated areas. If farmers are to enter the input efficiency stage, they will need a wider range of technical information enabling them to understand the scientific basis of the new technology and to better adapt that 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 and ensures the effective participation of farmers. Increased intensity and specialization in cropping systems will also require that research programs for commodities which happen to be grown in the same cropping system coordinate their work and communicate more effectively with each other. This is particularly true for rice and wheat research programs, because of the importance of both crops in major cropping systems. Most research systems in South Asia are presently too compartmentalized by commodity and discipline, and require significant changes in organization and incentive systems to meet the needs of research on the complex problems emerging in Asia's intensive irrigated systems.

Technology Transfer: Institutions and Policies

Public sector activities 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 invested substantially 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 (Desai 1988). This shift was facilitated by the increasing volume of inputs (especially fertilizer) being used and by 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%. 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 managerially intensive, 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 training and visit extension system promoted by the World Bank is now widely used in South Asia. Although it has met with some successes (Feder, Lau, and Slade 1987), this system remains directed toward promoting input use rather than promoting input efficiency. In addition, the effectiveness of extension is limited by continued poor contact with research, 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 in much of South Asia, which may increasingly limit farmers' capacity to use more complex technologies efficiently. 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. The evolution of information and skill systems is a major challenge for maintaining productivity increases and sustainability in the future.

Along with the efforts of research and extension, 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 rice and 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, government intervention has undoubtedly stabilized output prices and reduced the price risk to farmers in using purchased inputs (Krishna 1990). In the late 1980s both these policies are under review, and a trend toward eliminating input subsidies and freeing producer prices is emerging (Desai 1988). The removal of input subsidies is likely to accelerate the transition from input intensification to a stage of agricultural production that emphasizes greater input efficiency. However, without a corresponding change in producer price policies, which tend to maintain prices below import parity prices, removal of input subsidies may result in a decline in production (Desai 1988). Hence appropriate price policies are needed to complement institutional change in the new stage that emphasizes input efficiency.

Conclusions

Over the past 25 years, food grains in South Asia have experienced extraordinarily rapid and broad-based gains in productivity, especially wheat. Over this same period, the amount of new land available for agriculture has essentially been exhausted. 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 productivity in the 1960s and 1970s were stimulated by the widespread adoption of HYVs (especially for rice and wheat) and fertilizer, and by improvements in irrigation water supplies. In the 1980s, growth was largely the result of 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 production that would result from closing the yield gap should be sufficient to meet the demand for food grains 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 to enhance input efficiency, such as improved plant stand establishment, balanced fertilizer doses, and better weed control. Closing the yield gap thus requires a research strategy differing somewhat from past strategies, 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. In many areas where the exhaustive rice-wheat system is practiced, problems are appearing, especially in maintaining rice yields, and problems also seem to be emerging in large wheat growing areas such as the Punjab of Pakistan. Discussions of sustainability often emphasize a range of large scale problems such as groundwater depletion and salinization. But the evidence presented here suggests that more attention should be given to micro-level problems such as long term changes in soil fertility, soil 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 South 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 affecting 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 South Asia.

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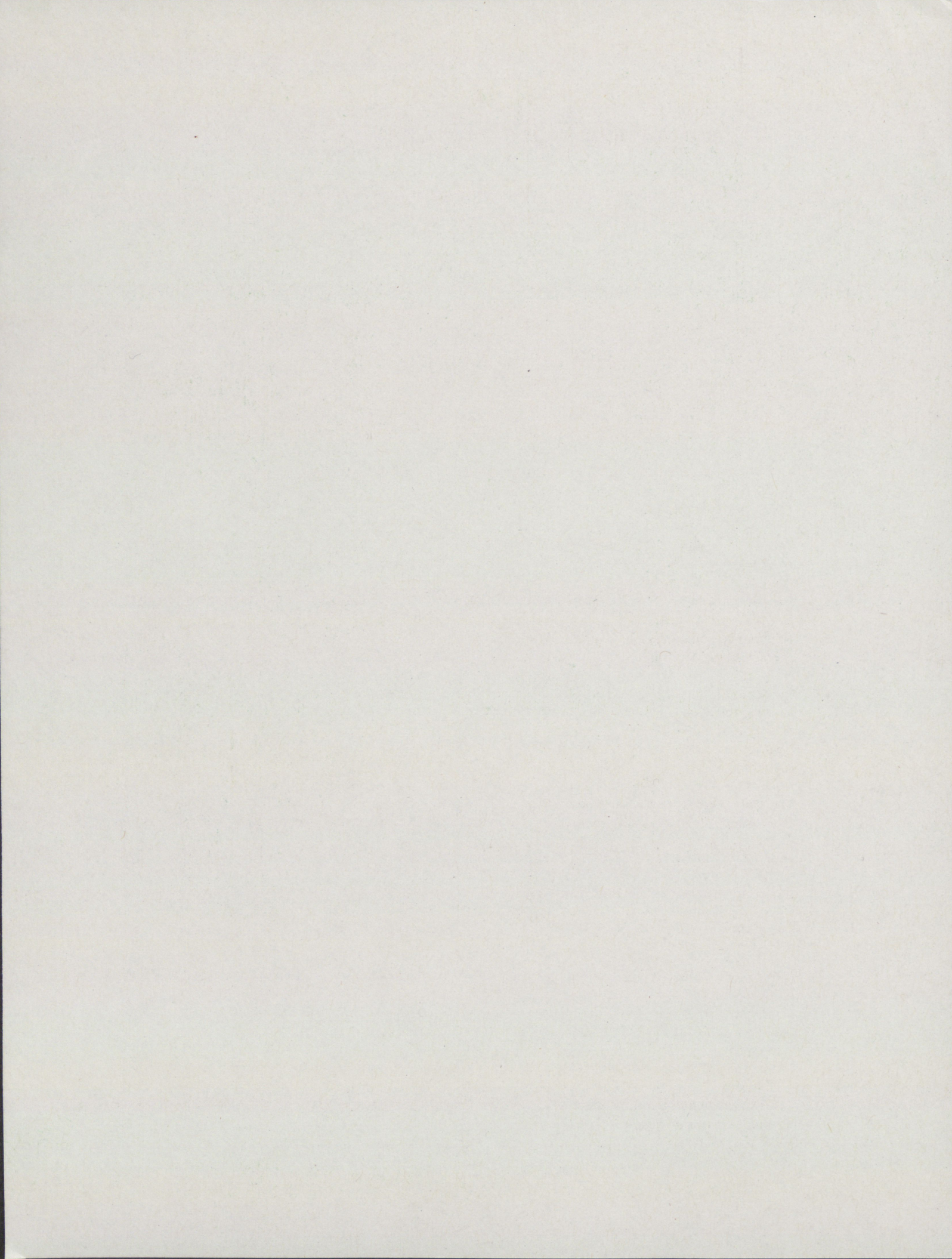
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