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Meeting South Asia's Future Food Requirements from Rice-Wheat Cropping Systems: Priority Issues facing Researchers in the Post-Green Revolution Era

Peter Hobbs and Michael Morris

NRG

Natural Resources Group

Paper 96-01

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Abstract: The importance of rice-wheat cropping systems in meeting present and future food needs in South Asia is reviewed. Evidence from a number of factor productivity studies, which analyze yield trends after adjusting for changes in levels of input use, suggests that growth in the productivity of South Asia's rice-wheat cropping systems is leveling off and, in some areas, declining. Some probable causes of this disturbing trend are considered, including soil-related factors (depletion of soil chemicals, soil physical problems from puddling soils for rice and/or repeated cultivation for wheat); problems relating to the quantity and quality of irrigation water; continuous and intensive cereal cultivation, which has increased the incidence of pests (including weeds) and diseases; and delayed planting of wheat following rice, a common practice in many rice-wheat systems, which severely reduces wheat yields. Changes in the organization and management of research, which are required to restore growth in productivity, are discussed in the final sections of the paper.

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Executive Summary

South Asia's food supply is dominated by rice and wheat, which account for about 90% of the region's total cereal production. Although growth in demand for these two crops is expected to ease as the population gradually stabilizes, future supplies of rice and wheat are difficult to forecast. Over the longer term, most analysts believe production increases will be hard pressed to keep pace with even modest growth in demand, fueled by rising incomes. Researchers thus face a formidable challenge in attempting to develop the improved production technologies that will be needed to feed large numbers of people from a dwindling land area.

This paper has four objectives:

- to demonstrate the crucial importance of rice-wheat cropping systems in meeting present and future food needs in South Asia;
- to present evidence suggesting that productivity growth in the region's rice-wheat cropping systems is leveling off and in some areas may be declining;
- to consider the causes of the apparent slowdowns in productivity growth; and
- to discuss changes that will be required in the organization and management of research if growth in productivity is to be restored.

South Asia's rice-wheat cropping systems, which cover 12 million hectares, are concentrated on the Indo-Gangetic and Brahmaputra flood plains and in the foothills of the Himalayas. About 32% of total rice area and 42% of total wheat area in the region comes under rice-wheat cropping sequences, which can also include legumes, oilseeds, fodder crops, vegetables, and sugarcane. Crop production is often linked to livestock production.

During the past three decades, growth in the area planted to rice and wheat in South Asia has slowed considerably. With traditional sources of area growth nearly depleted, further expansion in the area planted to these two crops is likely to be negligible. Future production gains therefore will have to come mainly from yield increases. Although average rice and wheat yields rose at about 2% per year between 1960 and 1990, evidence is accumulating to suggest that the impressive rates of yield growth achieved earlier are no longer being sustained. In some intensively cultivated zones, yields of rice and wheat have actually begun to decline.

Slower growth in yields is alarming, especially since the use of productivity-enhancing inputs now seems to be approaching saturation levels. Adoption of modern varieties (MVs) is virtually complete, and although farmers can look forward to realizing further genetic gains by replacing their older varieties regularly with new ones, the emphasis in plant breeding is increasingly shifting to characteristics other than yield *per se* (e.g., disease resistance, pest resistance, grain quality). Fertilizer use on rice and wheat is now close to optimal in many zones, and application of additional fertilizer is often unprofitable. Investment in irrigation has also become less attractive. Many older irrigation schemes need extensive rehabilitation, and construction costs for new schemes have risen. With traditional sources of productivity growth showing signs of exhaustion, future productivity gains will have to come from elsewhere.

Evidence that growth in the productivity of South Asia's rice-wheat cropping systems is slowing down has come from factor productivity studies, which analyze yield trends after adjusting for changes in levels of input use. In Bangladesh and India, factor productivity continues to increase in some areas, but in others it shows signs of leveling off or even declining. In Pakistan, factor productivity has fallen by more than 2% per year during the post-Green Revolution period.

Causes of the slowdown in productivity growth are still poorly understood. Soil-related factors are part of the problem. Soil chemicals can be depleted in intensively cultivated rice-wheat systems in which nutrient extraction is not always matched by nutrient input, while soil physical problems are caused by puddling of soils for rice and/or repeated cultivation for wheat. Problems relating to the quantity and quality of irrigation water have also affected productivity. Declining water tables force farmers to pump water from great depths, and many irrigated areas are prone to salinity and sodicity problems. Continuous and intensive cereal cultivation has increased the incidence of pests and diseases, while buildups of grassy weeds have become serious problems in some areas. Delayed planting of wheat following rice, a common practice in many rice-wheat systems, also severely reduces yield.

Agriculture in South Asia can be thought of as progressing through three phases of technical change: a "Green Revolution Phase," an "Input Intensification Phase," and an "Input Efficiency Phase." Many of South Asia's rice-wheat systems have entered the last of these three phases. Multidisciplinary, systems-oriented research is required to develop the sophisticated, site-specific management information needed to improve input-use efficiency in the context of ever more intensive cropping systems in which avenues for successful technical innovation are increasingly constrained.

The need for new technologies and information has implications for agricultural research. Not only does the organization of research need to be changed, but the management of research programs needs to be made more efficient. Objectives need to be more clearly defined and better prioritized, redundant programs need to be eliminated, and efficiency needs to be increased through consolidation. Unfortunately, the need for restructuring comes precisely at a time when donor assistance is declining and when many governments are reducing public support to agricultural research.

Meeting South Asia's Future Food Requirements from Rice-Wheat Cropping Systems: Priority Issues Facing Researchers in the Post-Green Revolution Era

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Introduction

As the twentieth century draws to a close, the challenge facing agricultural researchers is greater than ever. Global demand for food continues to grow steadily, with population growth adding 90 million new mouths to feed each year. Since most of the earth's arable land is already in use, additional food supplies will have to be produced by increasing food production from land that is currently being cultivated.[1] However, much of this land appears to be stretched to its limits, and in some areas there are signs that current levels of productivity cannot be maintained.

Nowhere is the challenge greater than in South Asia. Long-term forecasts of the region's food balances have been made by a number of analysts (for a summary, see McCalla 1994). On the demand side, a broad consensus prevails that a slowdown in population growth is expected to be offset by modest increases in income levels. Opinions differ as to when demand will eventually stabilize, but most analysts believe that annual growth in cereal consumption will average 2-2.5% until well into the twenty-first century.[2]

There is less agreement regarding prospects for future growth in food supplies, both for the world as a whole and for South Asia. Differences in projected rates of production growth stem primarily from disagreements about the sustainability of the natural resource base that supports agriculture, about future rates of productivity gains that may be achieved through technological innovation, and about government policies toward agriculture. At the pessimistic end of the spectrum, neo-Malthusians foresee a marked slowdown in cereal production growth as a result of rapid deterioration in the natural resource base and depletion of land and water resources (Kendall and Pimental 1994, Brown 1994, Brown and Kane 1994). Others are more sanguine, predicting that the demand for food eventually will be met, albeit with difficulty (Rosegrant and Agcaoili 1994, Islam et al. 1992). A few analysts are openly optimistic about long-run global food balances, arguing that there is little evidence to suggest that historical rates of productivity growth are slowing and hence no reason to assume that current rates cannot be maintained (Plucknett 1993, Mitchell and Ingco 1992).

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1 Of the earth's land area, only 24% (3.2 billion hectares) consists of arable land. Of the arable land, 1.3 billion hectares are classified as highly or moderately productive. Currently, 1.5 billion hectares are used for cropland, including most of the highly and moderately productive land (Buringh and Dudal 1987).

2 Some analysts predict that global population growth will stabilize as soon as 30 years from now (Seckler 1994). If this prediction is correct, growth in the demand for food would decline much more rapidly.

Depending upon the assumptions made about future rates of growth in demand and supply, it is possible to come up with widely divergent forecasts about future food balances in South Asia. However, the most likely scenario is that despite a gradual slowing of growth in demand for cereals, food grain production in South Asia will be hard-pressed to keep pace with growth in consumption requirements. This view, which is consistent with the latest projections of the International Food Policy Research Institute (IFPRI), foresees South Asia facing a regional cereals deficit averaging around 20-25 million tons per year by 2020 (Table 1). Two key assumptions underlying this projection are that the expansion of irrigated area will slow markedly and that crop response to additional use of fertilizer will decrease. It is important also to note the implicit assumption that current rates of investment in agricultural research will be maintained. Should investment in agricultural research decline (which many consider likely), food deficits could be considerably larger.

Whatever happens, it is clear that during the early part of the twenty-first century, South Asia's fortunes will be greatly influenced by developments in the agricultural sector, particularly in the rice and wheat cropping systems which account for the bulk of the region's cereal production. South Asia's rice-wheat systems will play a decisive role, not only in determining whether food security can be assured for more than one billion people, but also in providing productive employment and generating much-needed income for rural populations.

This review of the challenges facing rice-wheat cropping systems in South Asia has four principal objectives:

- to demonstrate the crucial importance of rice-wheat cropping systems in meeting present and future food needs;
- to present evidence suggesting that productivity growth in rice-wheat cropping systems is leveling off and in some areas appears to be declining;
- to consider the micro-level causes of stagnating productivity; and
- to discuss changes that will be required in the organization and management of research if growth in productivity is to resume.

Table 1. Supply and demand projections for rice and wheat, South Asia

	1990 population (million)	1990-2020 projected population growth (%)	1990 rice production[a] (000 t)	2020 projected rice production[a] (000 t)	2020 projected rice demand[a] (000 t)	2020 projected rice balance[a] (000 t)	1990 wheat production (000 t)	2020 projected wheat production (000 t)	2020 projected wheat demand (000 t)	2020 projected wheat balance (000 t)
Bangladesh	106.7	1.8	18,689	38,071	38,204	(132)	1,226	1,580	6,031	(4,450)
India	849.5	1.7	75,338	145,777	144,792	985	49,296	96,384	95,617	766
Nepal	18.9	1.8	2,580	3,814	3,407	407	860	1,401	1,357	44
Pakistan	112.4	2.8	3,448	6,207	5,309	898	14,413	27,463	42,914	(15,451)
South Asia[b]	**1,147.7**	**1.8**	**101,430**	**197,617**	**197,588**	**29**	**65,780**	**126,817**	**148,121**	**(21,303)**

Sources: Population data from World Bank (1992); rice and wheat data for Nepal from Thapa and Rosegrant (1995); and all other data series from Rosegrant, Agcaoili-Sombilla, and Perez (1995).

[a] Milled rice.

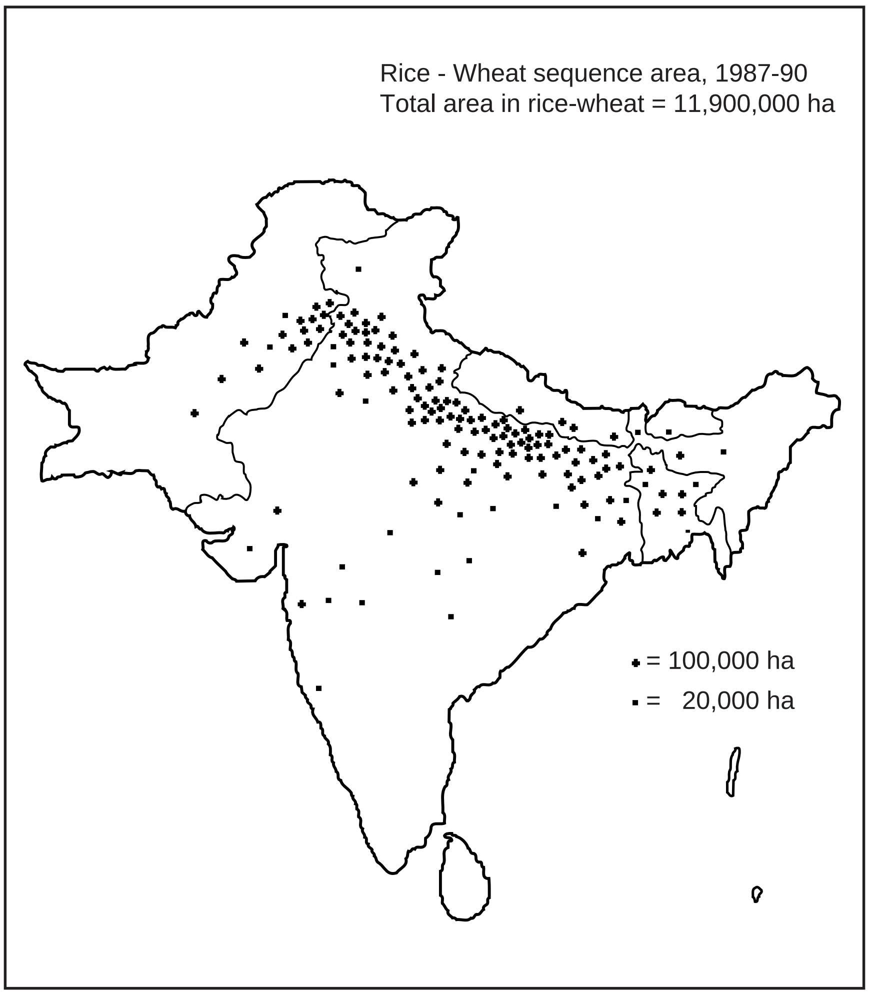
[b] Includes data for Bhutan and Sri Lanka.

Descriptive Overview of South Asia's Rice-Wheat Cropping Systems

Agriculture in South Asia has a long and rich history marked by a series of technological breakthroughs which today allow an exceedingly large number of people to be fed from a relatively small area. Two cereals — rice and wheat — contribute the bulk of the region's food supply and will continue to do so for the foreseeable future. South Asia's rice-wheat cropping systems, among the most highly evolved agricultural production systems on the planet, are often portrayed as highly productive systems which can serve as models for the rest of the world. Yet this portrayal is misleading, because these cropping systems are showing signs of declining productivity caused by resource degradation. What is especially alarming is the fact that the effects of resource degradation are often masked by increased input use, which can lead to the false impression that productivity is increasing when precisely the opposite may be true.

Area covered by rice-wheat cropping systems

The rice-wheat cropping systems of South Asia extend across the Indo-Gangetic flood plain and up into the Himalayan foothills. They span a vast area stretching from Pakistan's Swat Valley in the north to India's Maharastra State in the south, from the mountainous Hindu Kush of Afghanistan in the west to the Brahmaputra flood plains of Bangladesh in the east (Map 1).[3]



Map 1. Extent of rice-wheat cropping systems in South Asia.
Source: R. Huke and E. Huke.

[3] Although this paper focuses on rice-wheat systems in Bangladesh, India, Nepal, and Pakistan, the importance of these systems extends well beyond South Asia. In China alone, rice-wheat cropping systems cover an additional 10 million hectares.

The area covered by rice-wheat systems is difficult to state with precision.[4] Although the national crop reporting services of Bangladesh, India, Nepal, and Pakistan publish aggregate production statistics for rice and wheat, none publishes statistics specifically on rice-wheat cropping sequences. Area figures therefore must be pieced together based on subjective estimates made at the district level of the degree to which the two crops are planted in rotation. The district-level estimates can then be aggregated to arrive at national and eventually regional estimates (Table 2). In 1991, about 12 million hectares were under rice-wheat cropping systems in Bangladesh, India, Nepal, and Pakistan (Singh and Paroda 1994). Rice-wheat systems covered about 32% of the rice area and 42% of the wheat area in these four countries and accounted for between one-quarter and one-third of total rice and wheat production.[5]

The relative importance of rice and wheat varies between countries. In Bangladesh, rice is by far the dominant food staple, accounting for 93% of total cereal production and consumption. Wheat, traditionally a minor crop, has grown in importance since 1970 thanks to government efforts to promote production, but it remains of secondary importance in all but a few areas. Rice-wheat cropping systems cover an estimated 0.5 million ha, mostly in the northern and western "wheat belt" characterized by more elevated land and lighter, better-drained soils (Map 2). While only 7% of the area planted to rice is

Table 2. Area under rice-wheat cropping systems in South Asia, 1988

	Total rice area (million ha)	Total rice production (million t)	Total wheat area (million ha)	Total wheat production (million t)	Total rice + wheat area (million ha)	Total rice + wheat production (million t)	Percentage of wheat area located on land where rice is grown (%)	Percentage of rice area located on land where wheat is grown (%)	Rice-wheat area as percentage of total rice+wheat area (%)
Bangladesh	10.22	24.67	0.59	0.99	0.50	2.03	85	7	5
India[a]	40.90	100.11	23.56	50.04	9.12	38.58	42	33	21
Nepal	1.43	3.21	0.60	0.81	0.49	1.74	85	34	24
Pakistan	2.03	4.83	7.27	13.80	1.63	6.67	22	80	17
South Asia	**54.60**	**132.83**	**32.01**	**65.65**	**11.74**	**49.02**	**42**	**32**	**18**

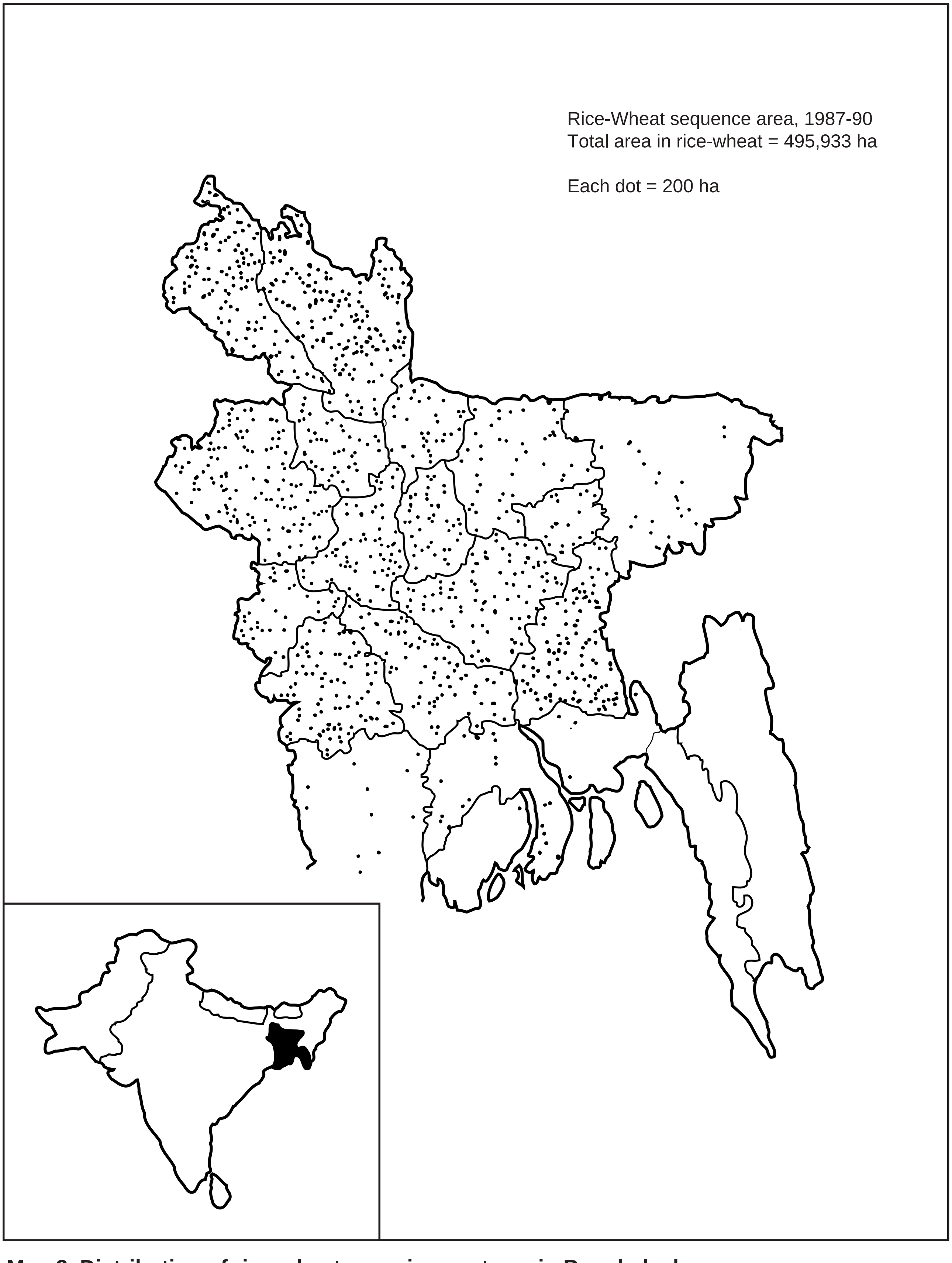
Source: Huke, Huke, and Woodhead (1994a, 1994b); Woodhead, Huke, and Huke (1994); and Woodhead et al. (1994).

Note: Since data on cropping patterns are not reported at the national level, the rice-wheat area for each country was estimated based on district-level data from a subset of districts for which data were available. The rice-wheat area in each district was estimated by multiplying the smaller of the district's rice or wheat area by a variable percentage estimated by researchers familiar with the district. District-level estimates were then aggregated to derive national estimates. The data are based on the average of the 1987 to 1989 data available in national program statistics.

[a] Includes Bihar, Madhya Pradesh, Haryana, Himachal Pradesh, Punjab, Uttar Pradesh, and West Bengal. Rice-wheat area in Assam, Gujarat, Jammu-Kashmir, and Maharashtra is not included.

[4] Since production statistics are not collected by cropping pattern, it is not possible to make a more precise estimate.

[5] Much of the descriptive information presented in this section was obtained from a series of atlases compiled by scientists working at IRRI, at CIMMYT, and in the national agricultural research programs of Bangladesh, India, Nepal, and Pakistan. See Huke, Huke, and Woodhead (1994a, 1994b); Woodhead, Huke, and Huke (1994); and Woodhead et al. (1994).



Map 2. Distribution of rice-wheat cropping systems in Bangladesh.
Source: Huke, Huke, and Woodhead (1994a).

located on land where wheat is also grown, approximately 85% of the much smaller area planted to wheat is located on land where rice is also grown.

India's highly diverse rice-wheat cropping systems are found on the Indo-Gangetic flood plain, in the Himalayan foothills, and in some irrigated zones further south (Map 3). With approximately 9.1 million ha under rice-wheat cropping systems, India dominates the regional production statistics. Approximately 33% of India's rice is grown in rotations involving wheat, while about 42% of wheat is grown in rotations involving rice. The states with the largest areas under rice-wheat cropping systems are Uttar Pradesh, Punjab, Haryana, Bihar, Madhya Pradesh, and Himachal Pradesh.

In Nepal, rice dominates the cereal economy, although as in Bangladesh wheat has made important inroads during the past two decades. Rice-wheat cropping systems cover an estimated 0.5 million ha and are distributed between the low-lying Terai and the more elevated mid-hills (Map 4). Nearly all wheat follows rice, whereas about one-third of the rice crop is followed by wheat.

In Pakistan, where wheat is the primary food staple, rice-wheat cropping systems cover about 1.6 million ha and are concentrated in the irrigated zones of Punjab and Sind and in the Himalayan foothills (Map 5). Approximately 22% of the nation's wheat is grown in rotations involving rice, whereas over 80% of the rice is grown in rotation with wheat. Most wheat in Pakistan is produced for domestic consumption, whereas rice (especially high-quality basmati rice) is a major export crop, about half of which is sold overseas.

Agroclimatic conditions

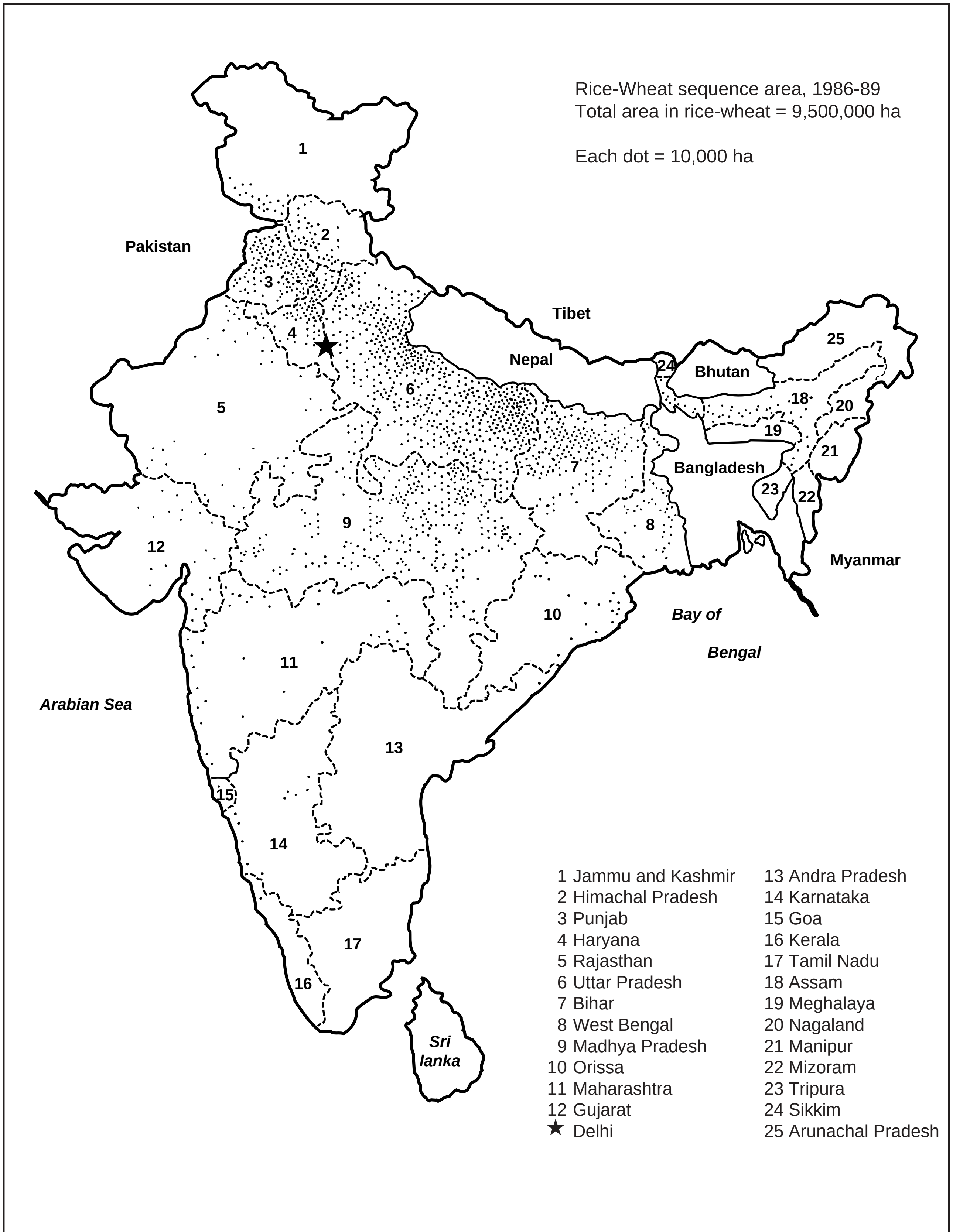
Most rice-wheat cropping systems in South Asia are located in areas featuring subtropical to warm-temperate climates, characterized by cool, dry weather during winter (when wheat is grown) and warm, humid weather during summer (when most rice is grown). Temperatures are higher to the east and south, reducing the length of the wheat season.

Annual precipitation is concentrated in the summer months. Although total annual rainfall tends to be greater in the east, winter rains are often heavier in the west. Irrigation is commonly used to supplement rainfall for both rice and wheat and is available in many areas from canals and/or tubewells.

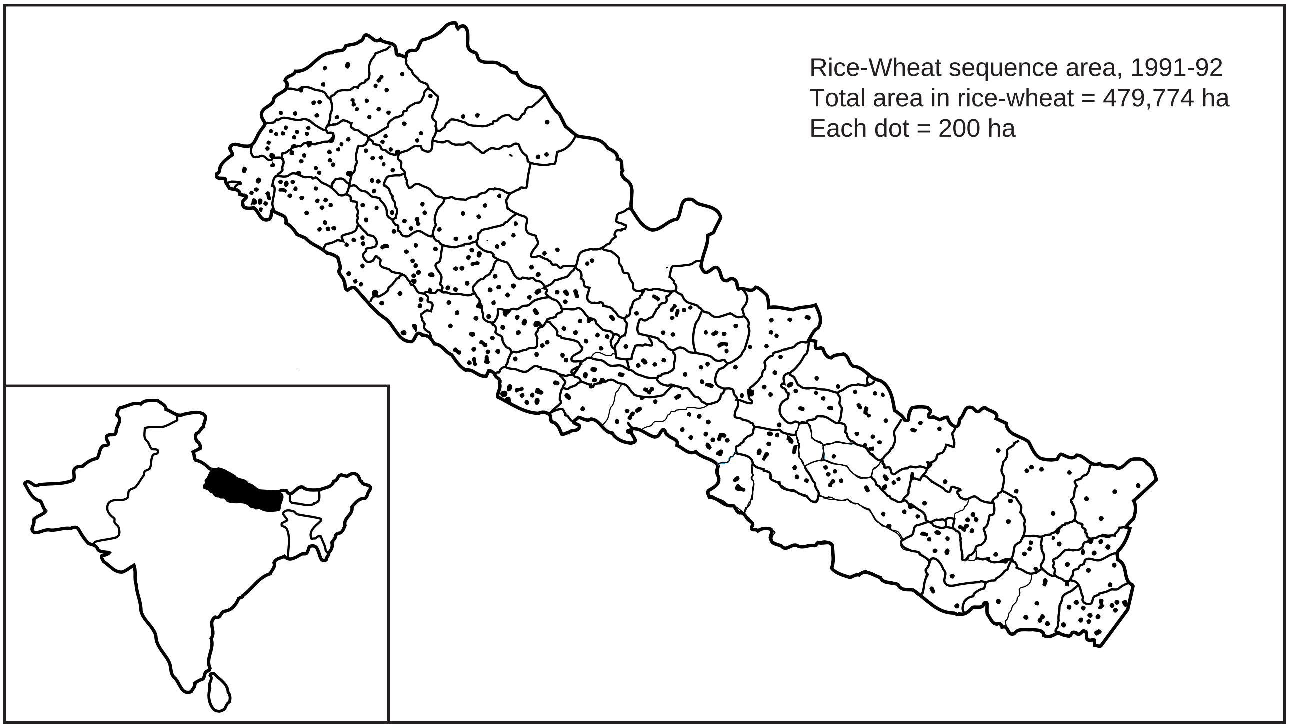
Soils tend to be highly variable. The calcareous soils of the Indo-Gangetic flood plain are generally basic (characterized by high pH levels), as opposed to the non-calcareous Brahmaputra and Jamuna flood plain soils of Bangladesh, which are more acidic. Free calcium carbonate is present in some of the Indo-Gangetic soils. Soil texture varies with local topography, with coarse soils often found on more elevated ridges and fine soils often found in low-lying basins. Most soils are very productive, although they require additions of nitrogen, phosphorus and, in some areas, micronutrients such as zinc.

Demographic characteristics of rice-wheat zones

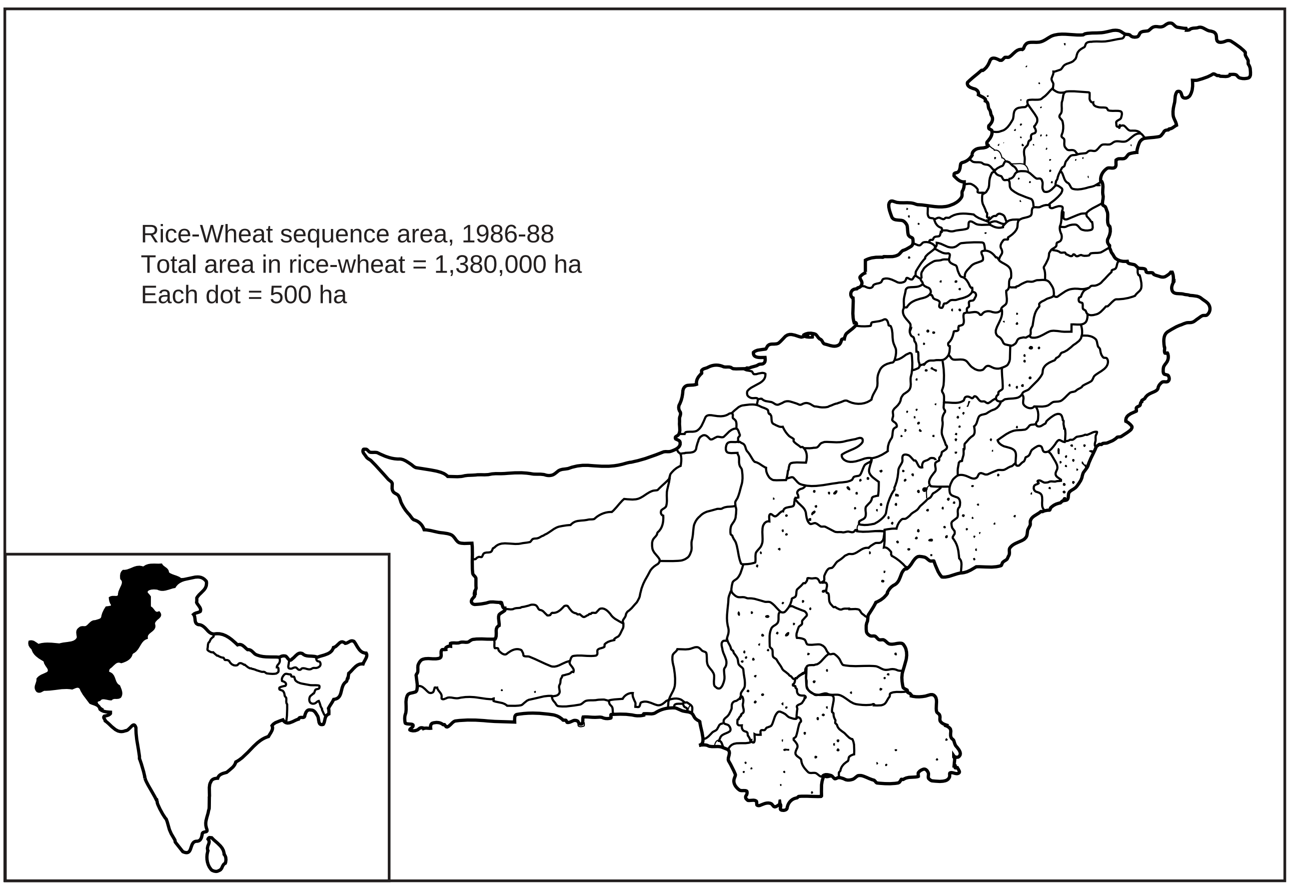
South Asia's rice-wheat belt is home to 600 million people, approximately two-thirds of whom are employed in agriculture. Although production and consumption statistics are not collected on the basis of specific cropping patterns, it is estimated that between 150 and 275 million people consume rice and/or wheat



Map 3. Distribution of rice-wheat cropping systems in India.
Source: Adapted from Woodhead et al. (1994).



Map 4. Distribution of rice-wheat cropping systems in Nepal.
Source: Huke, Huke, and Woodhead (1994b).



Map 5. Distribution of rice-wheat cropping systems in Pakistan.
Source: Woodhead, Huke, and Huke (1994).

produced in rice-wheat cropping systems.[6] In addition to the grain consumed at home, surplus production may be marketed to generate cash.

Population growth for South Asia as a whole currently exceeds 2% per year. Even if this rate slows as predicted to around 1.8% per year, the population living in rice-wheat-areas is likely to exceed 850 million by the year 2010. Income levels are extremely low. In 1992, average annual per capita GDP in South Asia ranged from US$ 170 in Nepal to US$ 420 in Pakistan (World Bank 1994). Incomes in rural areas which depend on agriculture are usually even lower than these national average figures.

In the past, agriculture represented the main source of employment for landless laborers in rural areas. More recently, urban industrial development and the attendant employment opportunities have offered the prospect of a better life in the cities, inducing many people to abandon rural villages in search of urban jobs. In some areas this has resulted in a reduction in the labor available for agricultural work and an increase in rural wage rates.

Rice-wheat cropping systems

Although all rice-wheat cropping systems by definition include rice and wheat, rice-wheat systems can vary tremendously. Temporal and spatial relationships between the two crops often differ: rice and wheat may be grown in the same plot in the same year, in the same plot in different years, or in different plots in the same year. While rice and wheat may be the only crops grown in a given plot, frequently other crops are also present, either associated with the rice and/or wheat (grown at the same time) or rotated with the rice and/or wheat (grown before or after). Crops commonly included in rice-wheat systems include oilseeds (mustard, rapeseed, sunflower); pulses (grasspea, mung bean, black gram, lentil); fodder crops (*berseem* clover, fodder sorghum, or pearl millet); vegetables; potatoes; sugarcane; and jute (Figure 1).

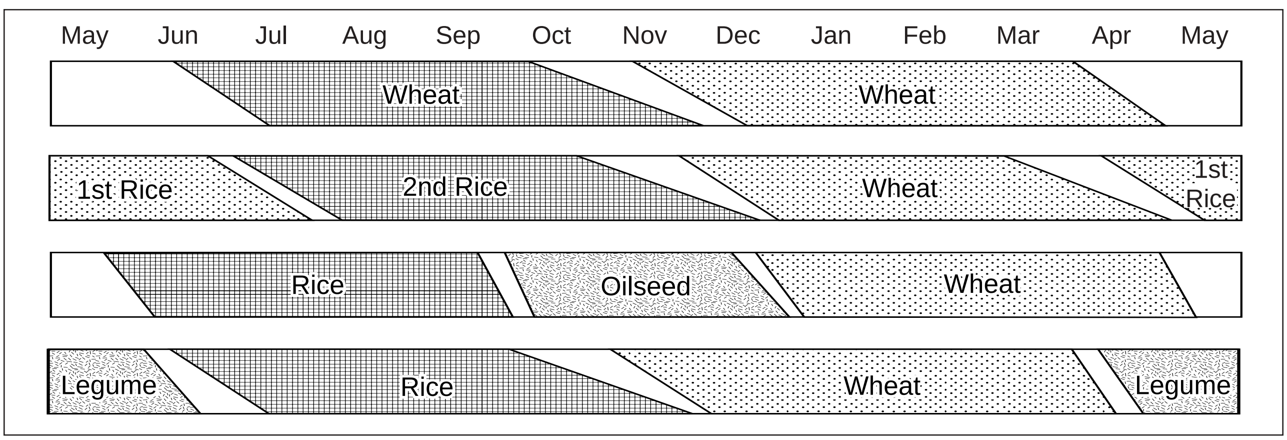


Figure 1. Common rice-wheat cropping patterns of South Asia.

Note: Substitutes for oilseeds (short-duration *Brassica* spp.) include potatoes, vegetables, and peas. Legumes include mung bean and green manures (e.g., *Sesbania* spp.); fodder sorghum or millet can substitute for legumes. Substitutes for wheat include *berseem* clover, lentils, grasspea, mustard, and rapeseed. Sunflower can also substitute for wheat, but it is planted in late January or early February. Jute can substitute for rice. Rice-wheat-sugarcane rotations that extend for several years are common in some areas.

[6] The number of people who consume rice and/or wheat produced in rice-wheat cropping systems was estimated based on: (a) the proportion of rice (and wheat) in total cereals consumption; (b) the proportion of rice (and wheat) production that comes from rice-wheat areas; and (c) the degree of overlap between the rice-consuming and wheat-consuming populations (P. Heisey, CIMMYT, pers. comm.).

Because of differences in numbers of crops and planting patterns, the intensity of rice-wheat systems can vary. Cropping intensity is often close to 200% in simple rice-wheat systems and can reach 300% or more in areas where land is scarce and the demand for food strong. Three-crop rotations typically include two short-duration rices followed by wheat, or a short-duration rice followed by a short-duration vegetable, potato, or oilseed planted before wheat. Two factors have been particularly important in enabling farmers to cultivate rice, wheat, and sometimes another crop on the same piece of land within the same year. First, irrigation has been instrumental in facilitating intensification. Irrigation breaks the traditional dependence on rainfall which in areas characterized by a single monsoon period restricts farmers to one cereal crop per year (or one rainfed crop and one additional crop grown immediately following the monsoon using residual soil moisture). Second, many modern varieties (MVs) of rice and wheat are short-duration, non-photosensitive varieties bred to mature more quickly than traditional varieties (TVs), which means they can be planted later or harvested earlier and thus fit more easily into intensive multicrop rotations.[7]

Almost all wheat varieties grown in rice-wheat zones consist of semidwarf MVs. Wheat MVs are preferred not only because they yield well and resist diseases, but also because they have a shorter growing cycle compared to most TVs. Rice varieties grown in rice-wheat zones are more variable. Although semidwarf MVs of rice have been extensively adopted in many areas, use of tall TVs is still common in some rainfed lowland and deep-water production environments where MVs may not be particularly well adapted. In some areas where livestock fodder is economically important, rice TVs may be preferred because of their superior fodder quality. Aromatic basmati rices (most of which are TVs) are grown in some areas because of their high market price, which more than offsets relatively low yields.

Farming systems in the rice-wheat belt tend to be characterized by a high degree of complexity and by a reliance on external inputs. In marginal production environments, lack of resources and limited technological options often foster the emergence of low-input farming systems in which rice and wheat cropping are well integrated into the larger household food economy. In favored production environments, farmers tend to have a more commercial orientation, and use of external inputs (especially inorganic fertilizer) is usually much higher. Everywhere, animals play a vital role, consuming the output of crop production (fodder, grain, straw); providing food and other products for the farm household (milk, meat, leather); sustaining the productivity of the land (organic fertilizer residues); and serving as a source of power (of fuel for cooking, of traction for tillage and transportation). The many links between cropping, animal husbandry, and other income-generating activities complicate the process of technology design, because changes to one part of the system carry implications for other parts.

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7 The term "modern varieties" (MVs) as used in this paper refers to semidwarf varieties of rice and wheat developed since 1960. "Traditional varieties" (TVs) refers to older varieties, including many varieties that have never been worked on by a formal plant breeding program. As Byerlee (1994) has pointed out, the term "modern variety" is something of a misnomer, since some MVs are now more than 30 years old. However, it is preserved here to maintain consistency with other publications on the subject. The term "high-yielding varieties" (HYVs), which is often used to refer to the same varieties, is equally inaccurate, since many semidwarf varieties were bred for characteristics other than yield potential.

Trends in Rice-Wheat Cropping Systems[8]

Area trends

During the past three decades, the area planted to rice in South Asia has increased fairly steadily, at a rate of about 0.7% per year (Figure 2). The expansion in rice area has been stimulated by a number of factors, not the least being the introduction of rice MVs beginning in the mid-1960s, which in many countries led to pronounced growth in the area sown to rice. While rice area has grown fairly steadily, the sources of growth have changed through time. During the late 1950s and early 1960s, rice area was expanded by bringing previously unused land under cultivation or by planting rice in areas previously used to grow other crops. During the 1970s and 1980s, expansion in rice area was fueled mainly by intensifying the cropping pressure on land that was already under cultivation, often following the conversion of rainfed land to irrigated land. In recent years, expansion of the land surface used for agriculture has all but ceased, and the proportion of cultivated land that is irrigated is approaching 100% in many heavily populated zones. As opportunities for further expansion dwindle, growth in rice area is expected to slow and eventually to cease altogether, which already seems to be happening in northwestern India (Chaudhary and Harrington 1993). With population growth continuing at well over 2% per year, the historical decline in area planted per capita is likely to accelerate (Figure 3).

The overall trend for South Asia is reflected in rice area growth patterns within the region's major rice-producing countries. In India, rice area grew steadily during the 1960s and 1970s, with the total area planted to rice increasing

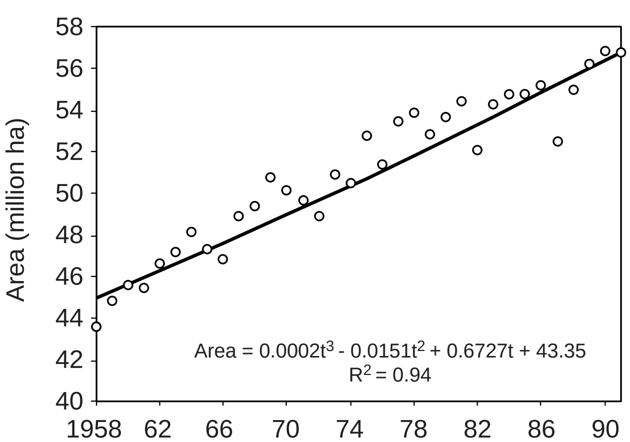


Figure 2. Rice area, South Asia, 1958-91.
Source: IRRI (various years).

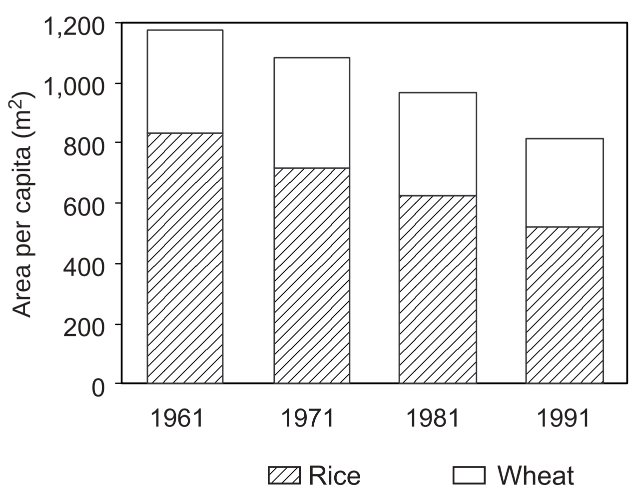


Figure 3. Rice and wheat area per capita, South Asia, 1961-91.
Source: FAO (various years).

[8] Because of considerable year-to-year variability in the data, area and yield growth rates calculated for specific periods tend to be extremely sensitive to the choice of years (i.e., shifting the starting or stopping point by a single year often greatly influences the results). For this reason, in discussing national and regional area and yield trends, we have tried to avoid mentioning average annual growth rates. To facilitate interpretation of the data presented in the figures, trend lines have been specified as third-degree polynomial functions, a flexible form which allows for two inflection points. Other specifications (e.g., linear, log-linear, piecewise linear) sometimes provide a better fit, but for the sake of consistency, the same specification was used throughout.

from about 34 million hectares in 1960 to just over 40 million hectares by 1980 (Figure 4b). Since 1980, growth in rice area in India has slowed, with the 1990s showing virtually no growth at all.[9] In Pakistan, the pattern has been similar: rice area grew steadily during the 1960s and 1970s before slowing during the 1980s and 1990s (Figure 4d). Bangladesh also experienced an early period of rapid growth in rice area during the 1960s and 1970s, followed by a slowdown during the 1980s and 1990s. However, in Bangladesh the slowdown has been less dramatic because of the large effect of *boro* rice, a crop whose importance was greatly stimulated by the rapid expansion of irrigation infrastructure beginning in the mid-1970s (Figure 4a). In Nepal, rice area continues growing at its long-term rate of about 1% per year and thus far shows no sign of slowing (Figure 4c).

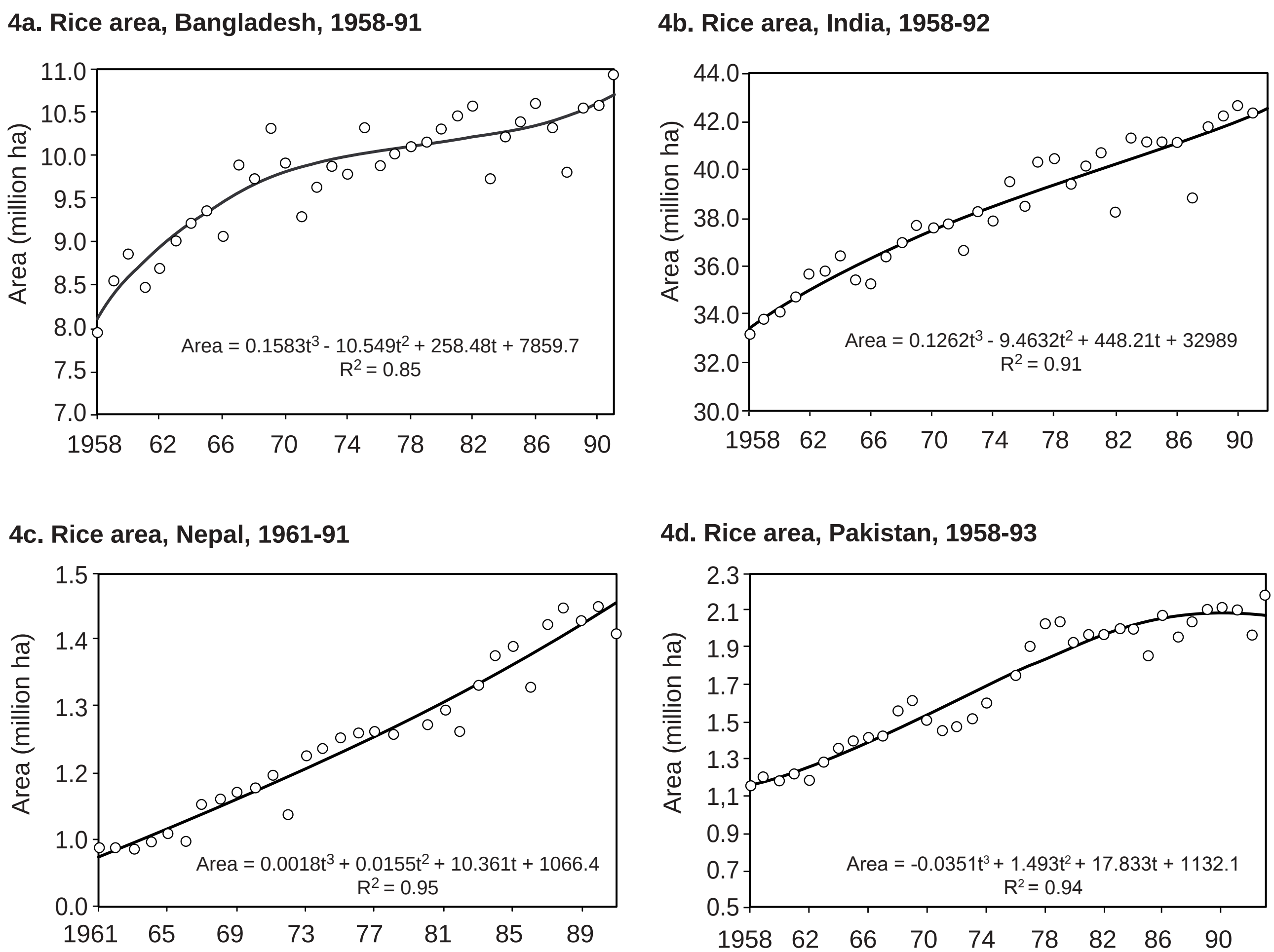


Figure 4. Rice area in Bangladesh, India, Nepal, and Pakistan.
Source: IRRI (various years).

9 Not unexpectedly in a country as large as India, the pattern of growth in rice area has varied considerably between states and sometimes even between districts within states. Numerous studies based on state- and district-level data have shown that the Green Revolution technologies made an initial dramatic impact in the irrigated tracts of northwestern India before spreading to less favorable production environments to the east and south. The sudden acceleration in growth in area evident in the national data presented here was often much more pronounced at the state and/or district level.

Wheat area in South Asia grew in a fashion similar to rice area during the past three decades, with a sudden acceleration in growth following the introduction of MVs and a subsequent — and even more pronounced — deceleration during the 1980s and 1990s (Figure 5). Prior to the introduction of MVs, wheat area in South Asia had been expanding slowly. Beginning in the mid-1960s, the introduction of wheat MVs (along with investment in irrigation) stimulated a surge in the rate at which wheat area increased. This rapid expansion continued for nearly two decades; only in the late 1980s did the rate of growth slow to earlier levels. As in the case of rice, growth in wheat area per capita has declined steadily (Figure 3).

The overall pattern of growth in wheat area for South Asia was reflected in the patterns of growth in wheat area within most of the region's major wheat-producing countries. In India, wheat area had been stagnant prior to the mid-1960s. Following the introduction of wheat MVs, wheat area expanded dramatically beginning in 1967 (Figure 6b). This growth spurt ceased almost as suddenly as it had started; since 1983, growth in wheat area in India has slowed markedly.[10] The pattern is similar in Nepal: after remaining flat through the late 1960s, wheat area suddenly expanded beginning in 1967, growing rapidly for nearly two decades before abruptly slowing in the late 1980s (Figure 6c). In Bangladesh, where wheat was not widely grown prior to the 1970s, wheat area experienced a decade of dramatic growth before slowing sharply during the 1980s and 1990s (Figure 6a).[11] In Pakistan, where wheat is the most important food crop, wheat area continues to expand at its long-term rate, and the expansion shows few signs of slowing (Figure 6d).

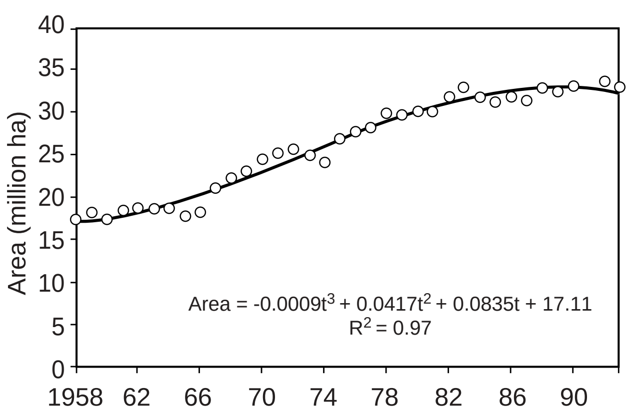


Figure 5. Wheat area, South Asia, 1958-93
Source: FAO (various years).

Across the region, the general picture has been one of an acceleration in the area planted to rice and wheat, followed by a pronounced slowdown in the rate of expansion. Although the timing of these events differed slightly between countries (and although in one or two cases the slowdown has yet to occur), generally the spurt in growth was concentrated in the period following the introduction of Green Revolution technologies (MVs, fertilizer, irrigation).

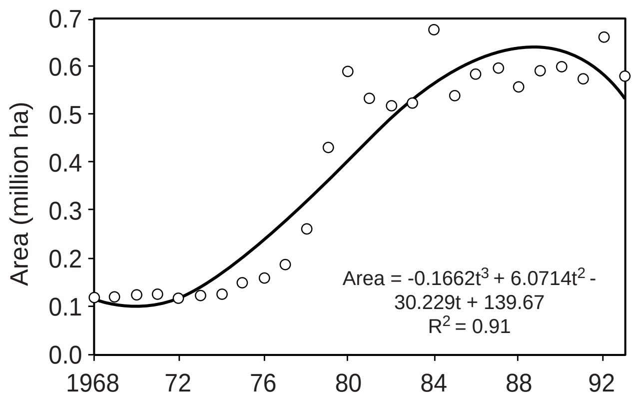
To what extent were changes in the area planted to rice and wheat (considered separately) mirrored by changes in the area under rice-wheat cropping sequences? Although no official statistics are published on rice-wheat sequences, estimates have been made for selected years for a geographic

[10] As in the case of rice, the sudden acceleration in growth in wheat area evident in the national data presented here was often much more pronounced at the state and/or district level.

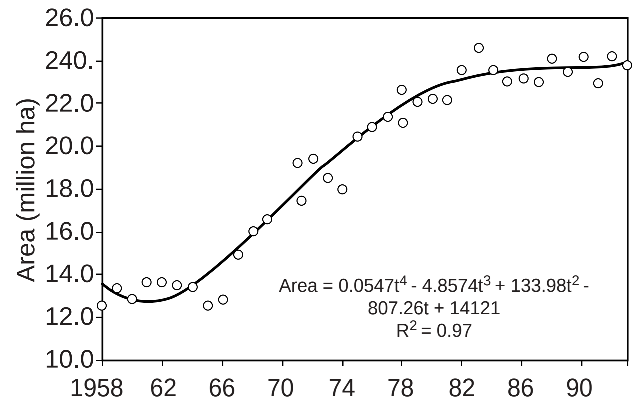
[11] An important factor underlying the sudden increase in wheat area in Bangladesh was the release of the variety Sonalika.

information system under development by a consortium of national and international agricultural research programs.[12] During the periods for which data are available (these periods vary from country to country), the area under rice-wheat cropping sequences expanded more rapidly (in percentage terms) than the areas planted to each crop (Table 3). This is hardly surprising, considering that growth in rice and wheat area (considered separately) has occurred during a period when the amount of arable land used for agriculture in South Asia has barely increased. In other words, farmers have expanded their rice and wheat area primarily by increasing the cropping intensity of land already under cultivation. Frequently farmers have achieved this objective by introducing a second cereal

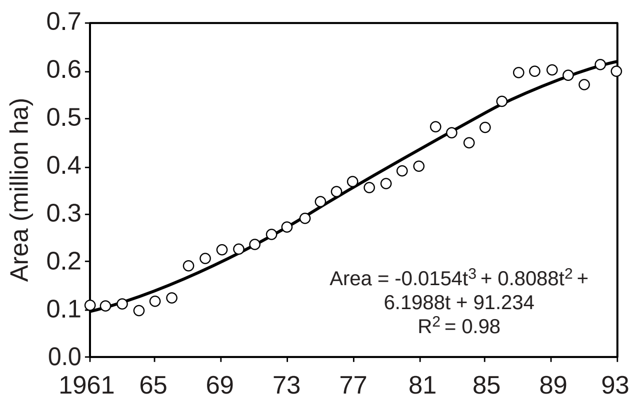
6a. Wheat area, Bangladesh, 1968-93



6b. Wheat area, India, 1958-93



6c. Wheat area, Nepal, 1961-93



6d. Wheat area, Pakistan, 1958-93

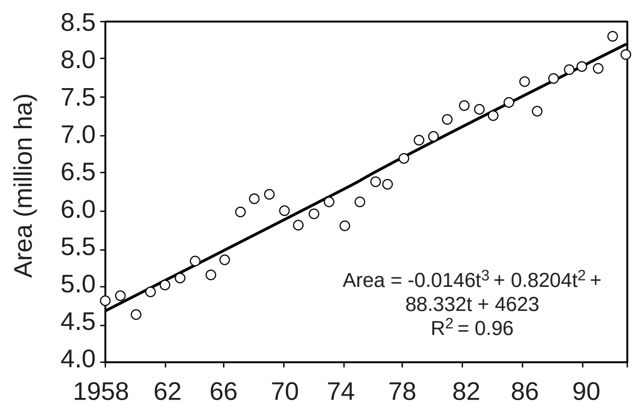


Figure 6. Wheat area in Bangladesh, India, Nepal, and Pakistan.
Source: FAO (various years).

[12] Since governments in South Asia do not report official statistics on cropping patterns, trends in the area under rice-wheat rotations must be estimated based on trends in the area planted to rice and trends in the area planted to wheat. In this report, the area under rice-wheat rotations in Bangladesh, India, Nepal, and Pakistan was estimated by multiplying national data on the areas planted to rice and wheat by coefficients obtained from surveys done in representative districts on the proportion of rice area that is also planted to wheat and the proportion of wheat area that is also planted to rice. Until official crop production statistics reported by each country include the area under specific cropping rotations, such *ad hoc* approaches will be necessary.

crop into the cropping pattern. Because rice is normally grown in the warm, humid *kharif* season and wheat in the cool, dry *rabi* season, the introduction of a second cereal crop often results in rice-wheat combinations.

Looking to the future, it is unclear how long rice-wheat area can continue to spread. Prospects for bringing new land under cultivation are limited; in fact, the physical supply of crop land is declining in South Asia as more and more surface area is converted to industrial or residential use.[13] Adoption of land-saving technologies will allow growth in cultivated area to continue for some time, even on a shrinking physical land base, but sooner or later the rate of expansion is bound to slow. The outlook is not promising, especially considering that cultivated area is expanding at a rate that lags considerably behind the population growth rate.

Table 3. Growth in area under rice-wheat cropping sequences, South Asia

	Rice-wheat area (million ha)	Rice-wheat area (million ha)	Annual growth (%)
Bangladesh	***1960-63***	***1987-90***	***1960-63 to 1987-90***
	0.05	0.50	8.6
India	***1959-62***	***1986-89***	***1959-62 to 1986-89***
	3.97	9.53	3.2
Nepal	***1975-76***	***1991-92***	***1975-76 to 1991-92***
	0.26	0.43	3.0
Pakistan	***1970-71***	***1987-88***	***1970-71 to 1987-88***
	1.02	1.38	1.7

Source: Calculated from data provided in Huke, Huke, and Woodhead (1994a, 1994b); Woodhead, Huke, and Huke (1994); and Woodhead et al. (1994).

Yield trends

With growth in rice and wheat area apparently flagging, attention is increasingly being directed to the second determinant of production: yield. What has been the history of growth in rice and wheat yields in South Asia?

Rice yields in South Asia increased noticeably following the introduction of MVs. In districts where MVs made their greatest impact, the effect was so pronounced that some observers described it as a "yield takeoff" (Plucknett 1993). The upturn in rice yields was evident even at the aggregate level; beginning in the late 1960s, average rice yields for the region as a whole began to rise steadily after having remained flat for many years (Figure 7).

Yield growth in individual countries has often differed from the regional pattern. In India, rice yields rose steadily from 1967 to 1987 before leveling off (Figure 8b). Although the slowdown in yield growth in India has occurred partly because more farmers grow low-yielding TVs that nevertheless command price premiums for their superior quality

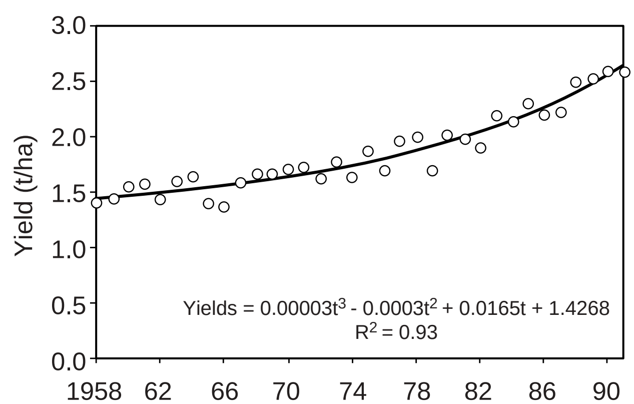


Figure 7. Rice yields, South Asia, 1958-91.
Source: IRRI (various years).

[13] This phenomenon is already evident in China, where hundreds of square kilometers of rice and wheat land are lost every year (Wehrfritz 1995).

(e.g., basmati), rice yields have stagnated even where no such varietal substitution has occurred. In Pakistan, the pattern has been similar. Rice yields experienced a sharp burst in growth beginning in 1967 before slowing to a barely positive long-term trend (Figure 8d). As in India, varietal substitution has contributed to slower growth in yields in Pakistan, although it does not explain it entirely. In Bangladesh, the picture is a bit different. Rice yields in Bangladesh began to rise during the early 1970s following the introduction of MVs. However, unlike elsewhere in the region, in Bangladesh the rate of yield growth has not slowed appreciably (Figure 8a). The continuing strong growth in rice yields in Bangladesh almost certainly has resulted from the increasing importance of high-yielding *boro* (winter) rice, which is grown under irrigation and which benefits from high levels of solar radiation and cooler temperatures during the growing season. In Nepal, rice yields have shown a modest upward trend characterized by considerable year-to-year variability (Figure 8c).

Wheat yields in South Asia have followed a growth pattern similar to that of rice yields, increasing sharply following the introduction of MVs and rising steadily ever since. From 1966 to 1990, average wheat yields for the region as a whole more than doubled, rising from just over 1.0 t/ha to about 2.3 t/ha (Figure 9).

As in the case of rice, wheat yield growth in individual countries has differed from the overall regional pattern. In India, where the

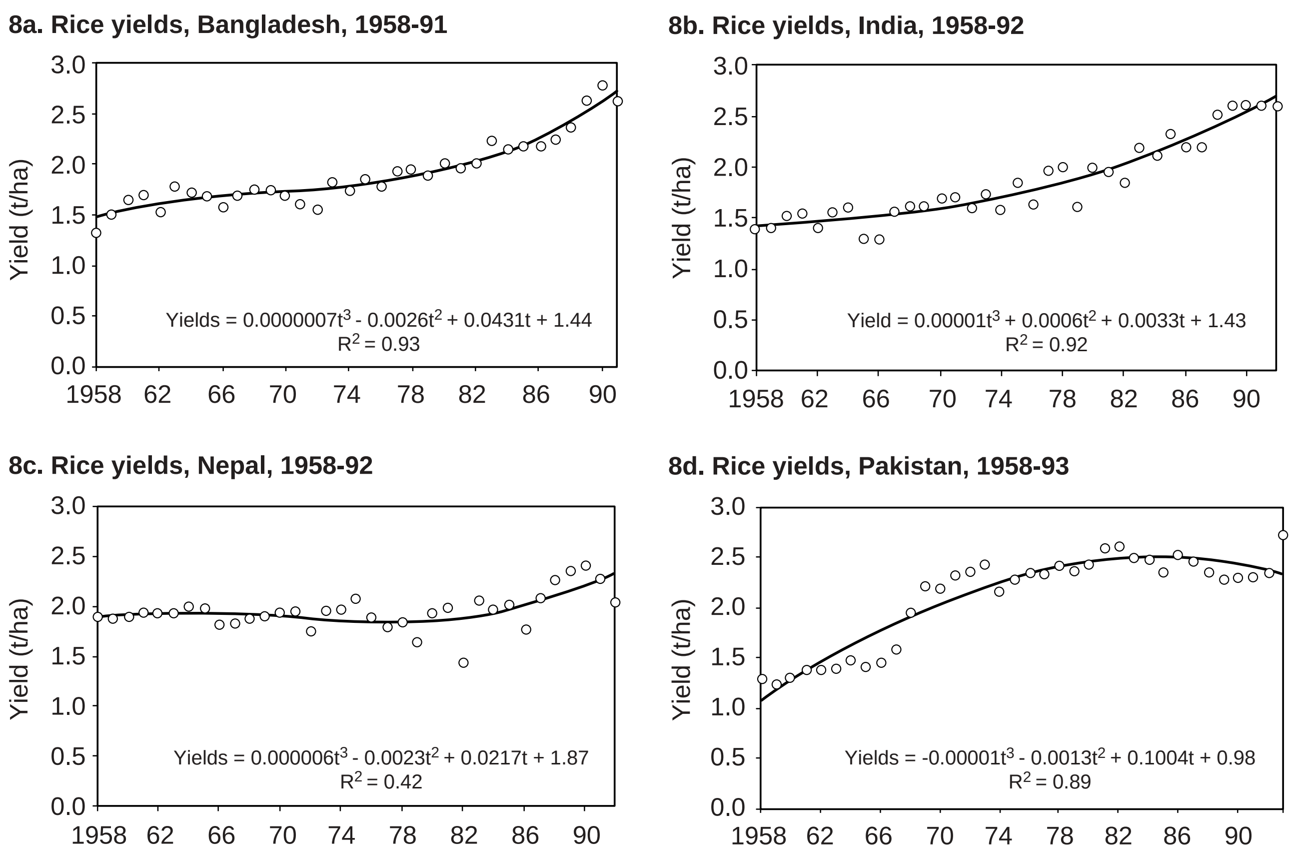


Figure 8. Rice yields in Bangladesh, India, Nepal, and Pakistan.
Source: IRRI (various years).

yield takeoff occurred in 1967, wheat yields have since grown steadily (Figure 10b). In Pakistan, the yield takeoff also occurred in 1967, although the yield growth that followed was less impressive (Figure 10d). In Bangladesh, the picture once again is a bit different. Wheat yields in Bangladesh accelerated sharply during the late 1970s and early 1980s as the result of government efforts to stimulate domestic wheat production. However, the growth in wheat yields ceased abruptly in the mid-1980s, and wheat yields actually fell in subsequent years (Figure 10a). The decline was caused by a combination of technical factors (e.g., conversion of prime wheat land to irrigation for use in *boro* rice production) and economic factors (e.g., removal of government subsidies on fertilizer). In Nepal, no clear yield takeoff is discernible; wheat yields have shown considerable year-to-year variability around a modest long-term upward trend (Figure 10c).

To summarize, yields of both rice and wheat increased substantially following the introduction of Green Revolution technologies. However, the timing of the initial takeoff in yields and the subsequent pattern of yield growth varied between countries and even between districts within countries. First to be

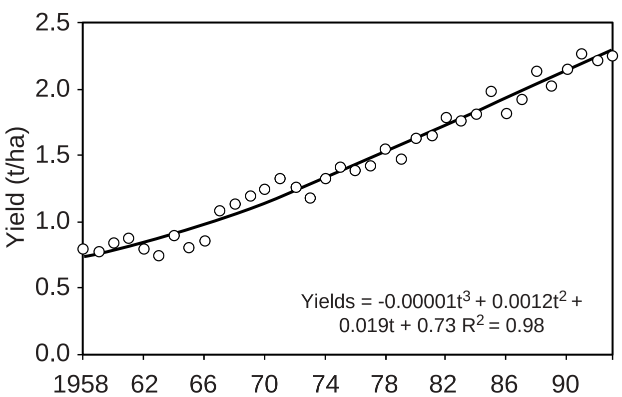


Figure 9. Wheat yields, South Asia, 1958-93.
Source: FAO (various years).

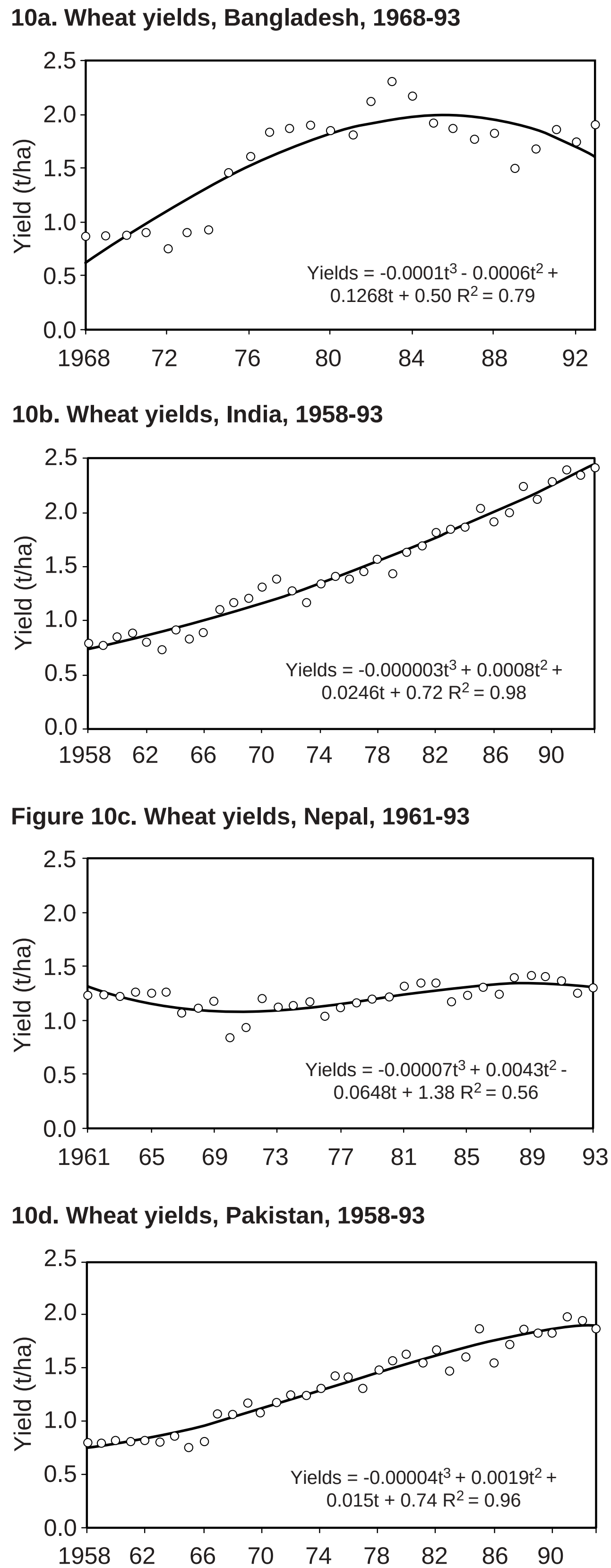


Figure 10. Wheat yields in Bangladesh, India, Nepal, and Pakistan.
Source: FAO (various years).

affected were favorable production environments in India and Pakistan, where yields rose dramatically beginning in the mid-1960s.[14] Following a lag, the Green Revolution technologies spread into less favorable production environments in both countries, but since adoption proceeded at a slower pace and was less extensive in these environments, yield increases were marginal (Figure 11). In Bangladesh and Nepal, where the Green Revolution technologies were relatively slow in arriving, the increase in rice and wheat yields became apparent only in the mid-1970s.

Impact on production

Widespread adoption of Green Revolution technologies and the resulting expansion in area planted to rice and wheat led to marked increases in rice and wheat production throughout South Asia (Table 4). In 1961, rice and wheat accounted for about three-quarters of total cereal production in the region; by 1991, the share of these two commodities had risen to nearly 90%. In some areas, the impressive production gains enabled food supplies to grow faster than the population, increasing production of cereals per capita and reducing dependence on politically undesirable imports, both commercial imports and food aid. Elsewhere, the production gains have not kept pace with population growth, and per capita production of rice and wheat have declined.

Input use trends

The yield gains achieved following the introduction of rice and wheat MVs were made possible partly by superior germplasm, partly by increased use of inputs (especially fertilizer and irrigation), and partly by interactions between inputs. In assessing prospects for future growth in the productivity of rice-wheat systems, it is important to appreciate the role played by these three key inputs in the past.

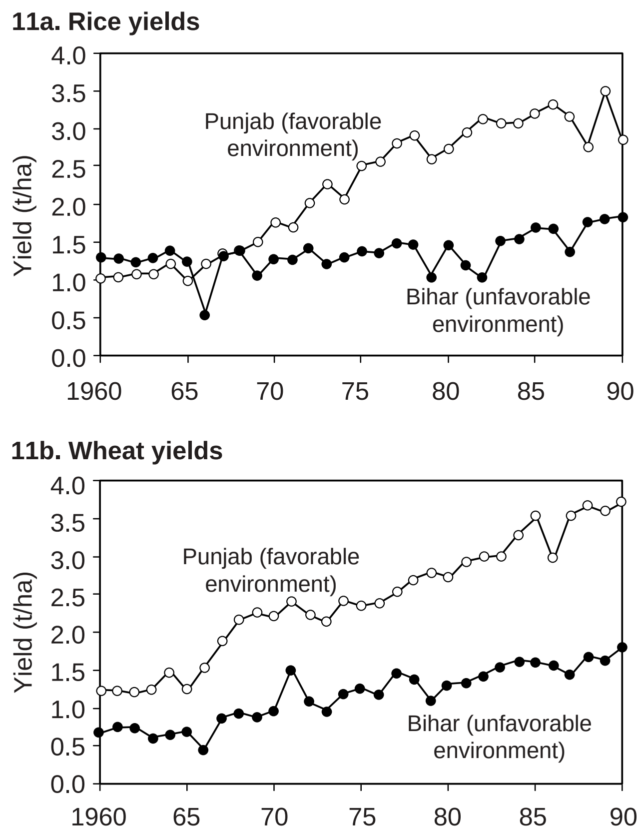


Figure 11. Rice and wheat yields in Punjab and Bihar States, India, 1960-90.
Source: Fertiliser Association of India (various years).

[14] Throughout this report, the term "favorable production environments" is used in a general sense to denote areas where rice and wheat yields are not unduly limited by agroclimatic constraints (e.g., moisture stress, heat stress, soil fertility imbalances). Examples of favorable production environments would be the irrigated zones of the Indian and Pakistani Punjabs. Conversely, the term "marginal production environments" is used to denote areas where rice and wheat yields are constrained by agroclimatic constraints, such as the mountainous zones of Nepal. Whether or not an environment is considered favorable or marginal for rice and/or wheat production depends not only on naturally occurring agroclimatic conditions, but also on technical and institutional factors (e.g., the presence or absence of a functioning irrigation system, the presence or absence of an effective fertilizer distribution network).

Improved germplasm — The Green Revolution in South Asian agriculture has been described often. During the late 1960s and early 1970s, semidwarf varieties of rice and wheat were introduced into India, Pakistan, Bangladesh, and Nepal. When grown with increased levels of fertilizer and an assured water supply, these MVs performed significantly better than the older, taller varieties they replaced, leading to substantial production increases and higher incomes for millions of farmers who adopted the technology.

The salient feature of the early rice and wheat MVs — achieved largely through plant breeding — was their increased yield potential. By incorporating dwarfing genes, plant breeders developed shorter, stronger plants which were able to produce more seed than the old, tall TVs and whose stems were strong enough to support additional grain weight. A less visible feature bred into MVs was their resistance to the pests and diseases that limited yields of many TVs.[15] Since the original MVs were introduced, subsequent generations of MVs have been released, offering higher yield potential, improved pest and disease resistance, better grain quality, and other desirable characteristics.[16]

Rice and wheat MVs spread rapidly throughout many of the irrigated districts where rice-wheat cropping is concentrated. These varieties spread more gradually into less favorable environments, as evidenced in India by steady growth in the proportion of the area planted to MVs, which has continued into the 1990s (Figure 12). Adoption of MVs has been more extensive in wheat than in rice because certain high-quality TVs of rice, such as the

Table 4. Rice (paddy) and wheat production (million t) in South Asia, 1950-90 (three-year averages)

Rice production	**1950-52**	**1960-62**	**1970-72**	**1980-82**	**1990-92**
Bangladesh	10.9	14.1	15.6	20.9	27.1
India	32.4	49.2	62.3	77.0	109.4
Nepal	2.5	2.3	2.2	2.3	3.1
Pakistan	1.2	1.6	3.4	5.0	4.8
South Asia	**47.0**	**67.2**	**83.5**	**105.2**	**144.4**
Wheat production	**1950-52**	**1960-62**	**1970-72**	**1980-82**	**1990-92**
Bangladesh	<0.1	<0.1	0.1	1.1	1.1
India	6.7	11.3	25.0	38.9	55.7
Nepal	<0.1	0.1	0.2	0.4	0.8
Pakistan	3.1	4.0	6.9	11.7	15.8
South Asia	**9.8**	**15.4**	**32.2**	**52.1**	**73.4**

Sources: Rice data from IRRI (various years); wheat data for India from Fertiliser Association of India (various years); data for Nepal from Ministry of Agriculture (various years); data for Pakistan from Ministry of Agriculture (various years) and PARC (n.d.); data for Bangladesh from Bangladesh Bureau of Statistics (n.d.).

15 The widely held belief that rice and wheat TVs were more resistant than MVs to diseases and insect pests is incorrect. In fact, the opposite is true. For example, many rice TVs were highly susceptible to blast and tungro virus, diseases that cause few problems today because of the incorporation of host plant resistance into MVs through breeding. Similarly, stem rust was a major disease of many wheat TVs, but because of the incorporation of *Sr*34 resistance genes into MVs, this disease rarely causes yield losses today.

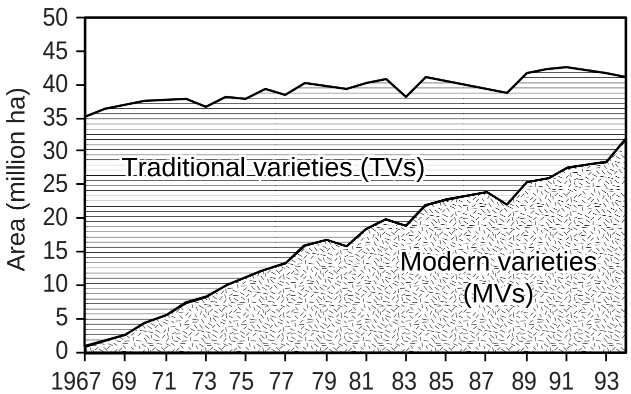
16 Most of the original semidwarf rice MVs were developed at the International Rice Research Institute (IRRI), and most of the original semidwarf wheat MVs were developed at the International Maize and Wheat Improvement Center (CIMMYT).

basmati varieties grown in parts of India and Pakistan, remain quite popular. The success of rice and wheat MVs in marginal environments has not always been recognized, perhaps because adoption proceeded more slowly and because the effect on yields was less dramatic there.

Fertilizer — Since MVs express their full yield potential when soil fertility is high, many farmers who adopted MVs found it profitable to invest heavily in inorganic fertilizer.[17] The use of fertilizer on rice and wheat soared throughout South Asia following the arrival of MVs (Figure 13). Fertilizer use was further encouraged by a sustained decline in global fertilizer prices, which governments were happy to pass on in the form of lower retail prices. As a result of the sharp increase in fertilizer use, fertilizer application levels in many districts are now at or above recommended levels (Table 5).

Water control — The superior performance of MVs soon stimulated increased investment in irrigation, since high yields were critically dependent on assured water supplies. The late 1960s and early 1970s saw an unprecedented surge in investment in irrigation throughout most of South Asia. When rice and wheat MVs were introduced in the mid-1960s, less than one-quarter of the area planted to rice and about one-half of the area planted to wheat in South Asia was irrigated. By 1990, about one-half of the area planted to rice and over three-quarters of the area planted to wheat was irrigated.[18] Growth in irrigated rice and wheat

12a. Adoption of rice MVs



12b. Adoption of wheat MVs

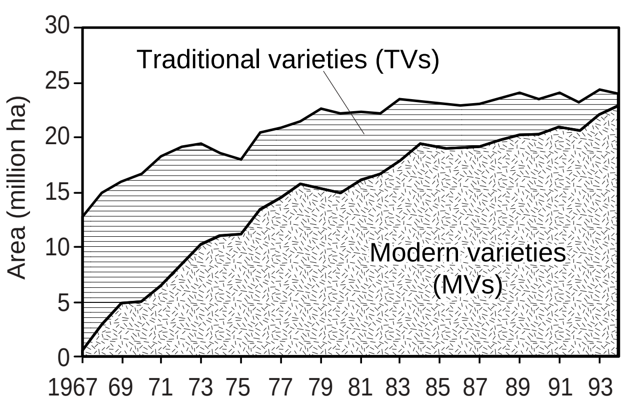


Figure 12. Adoption of rice and wheat MVs, India, 1967-94.
Source: Fertiliser Association of India (various years).

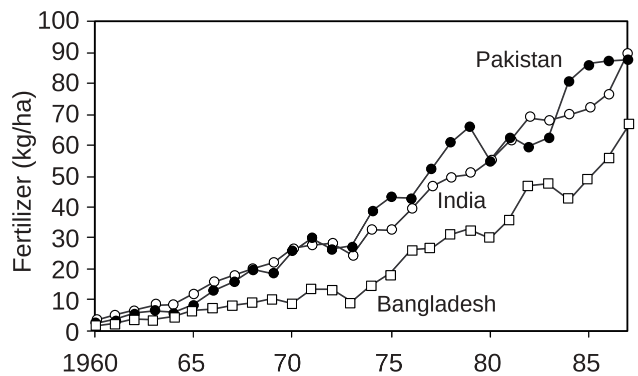


Figure 13. Fertilizer applied to rice in Bangladesh, India, and Pakistan, 1960-88.
Source: IRRI (various years).

[17] Contrary to the conventional wisdom, MVs grown without added fertilizer sometimes perform better than TVs, although the yield difference is sometimes small.

[18] In interpreting these figures, it is important to keep in mind that a significant proportion of the area classified as "irrigated wheat area" is only partially irrigated. In many areas, even though irrigation facilities are in place, water is available only during part of the cropping season.

area continues (Table 6), reflecting both ongoing conversion of rainfed land to irrigated land (Figure 14), as well as displacement by rice and wheat of other, less profitable crops.

Public and private sector investment in irrigation infrastructure continues to fuel expansion in irrigated area throughout South Asia. However, the incentives to invest in irrigation facilities have declined for at least two reasons. First, many irrigation systems have become degraded through lack of maintenance, so a considerable portion of irrigation investment now must be devoted to rehabilitating existing systems, rather than to constructing new ones. Second, further expansion of irrigation capacity requires that water control structures be constructed in increasingly remote areas, which tends to be extremely costly. With global prices of rice, wheat, and maize nearing historic lows, the returns to cereal production are often too low to justify installing irrigation facilities exclusively for grain production. Opportunities for profitable investment still exist, but improved impact assessment procedures will be needed to identify them (Rosegrant and Svendsen 1993).

Thirty years after the onset of the original Green Revolution in South Asia, it is becoming increasingly clear that the engine of growth is running out of steam. Modern varieties, fertilizer, and irrigation offer increasingly limited prospects for raising yields in the future, especially in areas where adoption of these inputs is already extensive.[19] Evidence for this conclusion comes from a number of

Table 5. Fertilizer use on rice and wheat in selected districts of India

Rice	**1970-71**	**1990-91**
Punjab (kg N/ha)	87	137
Haryana (kg NPK/ha)[a]	40	170
Wheat	**1970-71**	**1990-91**
Punjab (kg N/ha)	54	172
Haryana (kg NPK/ha)[a]	40	180

Source: Chaudhary and Harrington (1993), Gill (1992), and Sidhu and Byerlee (1990).
[a] Total of nitrogen (N), phosphorus (P), and potassium (K).

Table 6. Long-term trends in irrigated rice and wheat area, South Asia, 1950-90

Crop and time period	Irrigated area (000 ha) Bangladesh	India	Nepal	Pakistan	Total
Rice					
1949-51	120	9,844	na	967	1,091
1959-61	305	12,522	na	1,200	14,027
1969-71	958	14,207	na	1,527	16,692
1979-81	1,276	16,787	188	1,981	20,232
1989-91	2,530	19,200	350	2,087	24,186
Wheat					
1949-51	na	3,575	na	3,424	6,999
1959-61	na	4,170	na	3,826	7,996
1969-71	na	8,763	na	4,898	13,661
1979-81	170	15,173	na	5,374	20,717
1989-91	273	18,000	na	6,429	24,702

Source: IRRI (1991); Government of Pakistan (various years).
Note: na = not available.

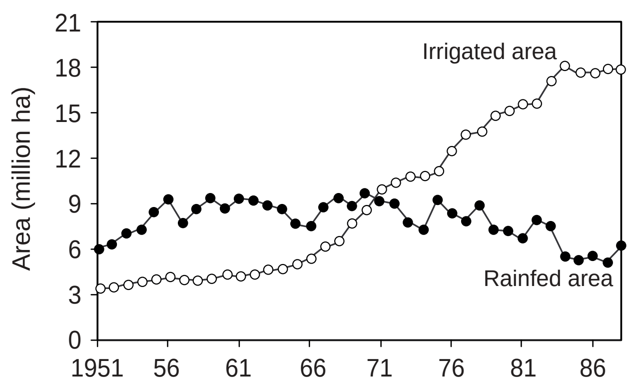


Figure 14. Rainfed and irrigated wheat area, India, 1951-88.
Source: Fertiliser Association of India (various years).

[19] Although future generations of MVs are unlikely to deliver yield increases which are proportionally as large as those delivered by the first generation of MVs, regular replacement of older MVs by newer ones should help farmers to maintain current high yield levels even as older MVs lose their resistance to diseases and pests. This benefit is extremely important and should not be overlooked.

intensively cultivated districts in northwestern India and northeastern Pakistan, where growth in rice and wheat yields has slowed noticeably during the past two decades, even though farmers have replaced older MVs with newer ones and have tripled fertilizer doses.[20] Although MVs, fertilizer, and irrigation do have the potential to deliver productivity gains in areas where their use is still suboptimal (e.g., eastern India, much of Bangladesh and Nepal), in the heart of the South Asian grain belt where rice-wheat cropping systems are most productive, these traditional sources of productivity growth are largely exhausted.

Trends in factor productivity

When the performance of agricultural production systems is assessed, yield trends are often used to measure changes in overall productivity. However, yield trends can be misleading when the quantity and/or quality of inputs changes significantly through time. Changes in productivity can be assessed more accurately using measures that take into account changes in input use.

Total factor productivity (TFP) studies — Changes in the productivity of agriculture are frequently evaluated using some index of total factor productivity (TFP). Various methods have been proposed for measuring TFP, all of which relate changes in agricultural output to changes in the use of inputs (see Christiansen 1975, Christiansen and Jorgenson 1970, Ball 1985, Antle and Capalbo 1988, and Barnett et al. 1994). When TFP is observed to increase through time, this trend is interpreted as evidence of productivity growth attributable to factors other than increases in the amounts of inputs used. Such factors can include technological change, changes in the quality of inputs, and/or changes in the physical or economic environment.

Originally conceived as a tool for measuring production efficiency over short periods, TFP indices have received new attention in recent years as indicators of the long-term sustainability of agricultural systems. This use of TFP indices was first proposed by Lynam and Herdt (1989), who pointed out that any sustainable production system would have to be characterized by a non-negative trend in TFP over an extended period. Others have subsequently built upon this idea by attempting to broaden the range of inputs and outputs reflected in the TFP index, for example by including environmental and social costs and benefits not usually considered in short-run productivity analysis, including long-term effects and off-site effects.[21] Although this work is still in its initial stages, important progress has been made in thinking through conceptual issues and in proposing innovative approaches for expanding the conventional indices (for example, see Steiner and Herdt 1995, Ehui and Spencer 1990, Whitaker and Lalitha 1993, and Harrington, Jones, and Winograd 1994).

One widely used TFP index is the chain-linked Tornqvist-Theil approximation to the Divisia index (or Tornqvist-Divisia index), which is relatively simple to calculate and easy to interpret. Although the theoretical underpinnings of the Tornqvist-Divisia index are conceptually straightforward, empirical calculation of the index may be complicated by

[20] Evidence cited by Rosegrant and Pingali (1994) suggests that similar yield stagnation has occurred in intensively cultivated rice-rice systems.

[21] Since the effects of resource degradation can for a long time be masked by technical change, TFP indices as they are currently calculated (i.e., omitting many environmental costs) are usually inadequate as indicators of sustainability.

any number of practical difficulties, including the accurate measurement of production inputs and outputs (particularly for individual commodities, since disaggregated statistics are rarely available); the valuation of production inputs and outputs (since market prices are often distorted by policies and/or market failures); and definition of the boundaries of the system being analyzed (since TFP may be calculated at the plot level, the farm level, the village level, the district level, the national level, the regional level, and so on).

Quite a few country-level studies in South Asia have reported TFP trends for the entire agricultural sector. Analyzing the agricultural sector as a whole simplifies the data requirements, since inputs and outputs need not be disaggregated by commodity. On the other hand, the results are less useful than commodity-specific studies, since productivity increases realized in one part of the agricultural sector can conceal productivity decreases occurring in another part. Studies of TFP focusing on the agricultural sectors of individual countries in South Asia have produced inconsistent results, in part because of methodological differences. For India, Evenson and McKinsey (1991) found little evidence that TFP declined between 1956 and 1984, a finding subsequently corroborated by Pray (1991) and by Rosegrant and Evenson (1992) in studies covering slightly different periods. For Pakistan, Evenson and Bloom (1993) reported evidence of a sharp decline in TFP during the post-Green Revolution period (1975-85), but since this study assumed a fixed share for land, the results were biased downwards and in fact may not have been all that different from those reported for India.

Studies of TFP focusing specifically on rice-wheat cropping systems are less common. Noteworthy among these has been the work by Ali and Velasco (1994) on productivity trends in the Punjab and Sind of Pakistan during the 1970s and 1980s. Total factor productivity in rice-wheat cropping systems fell during each of the two decades, with the decline in TFP averaging more than 2% per year in both study zones during the most recent period (Table 7).[22] Ali and Velasco attribute the decline in TFP to the deterioration of resources and argue that if this trend continues, more and more inputs will be required to maintain current output levels. They conclude pessimistically that current production practices are consuming resources which otherwise would remain available for future generations.

Evidence of declining productivity in intensively cultivated rice-wheat systems also has been reported by Cassman and Pingali (1995), who calculated TFP indices for 1970-88 using data collected in Ludhiana District in the Indian state of Punjab. Cassman and Pingali found that TFP increased steadily until the mid-1970s, when it leveled off for about a decade

Table 7. Trends in total factor productivity for rice-wheat cropping systems, Pakistan, 1970-79 and 1980-89

Province	1970-79	1980-89
Punjab (% annual growth)	-2.00**	-2.90**
Sind (% annual growth)	-0.24	-2.60*

Source: Ali and Velasco (1994).
Note: *,** indicate significance at the 5% and 1% level, respectively.

[22] Because Ali and Velasco used an analytical framework which did not explicitly incorporate changes in land use, their results are not directly comparable with some of the other results cited earlier and should therefore be interpreted with caution.

before beginning slowly to drop off. Based on extensive analysis of soils data, Cassman and Pingali attribute the decline in TFP to changes in the physical and chemical properties of repeatedly flooded and dried rice-wheat soils; these changes reduce the soils' nitrogen-supplying capacity and inhibit the efficient uptake of nitrogen by rice and wheat plants.

In addition to the relatively few TFP studies that have focused on rice-wheat systems, other studies have focused on rice or wheat separately. No attempt will be made here to review all of these. However, it is worth citing one or two to provide some idea of the accumulating evidence on productivity changes in areas where the Green Revolution made its greatest impact.

Sidhu and Byerlee (1991) estimated productivity changes for wheat in the Indian Punjab during the 1970s and 1980s. They concluded that despite consistent intensification of input use, productivity gains approaching 2% per year were achieved throughout the period of analysis. These productivity gains can be attributed in roughly equal proportions to the adoption of land-saving technology (e.g., MVs, fertilizer) and the adoption of labor-saving technology (e.g., machinery). Although Sidhu and Byerlee discerned no signs that the high productivity levels achieved by the late 1980s are in jeopardy, they warn that future sources of productivity gains capable of increasing TFP at rates equal to those achieved in the past are not evident.

Mohan Dey and Evenson (1991) examined productivity trends in rice, wheat, and other crops in Bangladesh from 1952 to 1989. These authors observed that slowdowns in the rate of yield growth were not necessarily attributable to biological deterioration of MVs or to environmental degradation; rather, declines in average yields were probably inevitable as MVs spread into marginal lands of lower production potential. Furthermore, the decline in yield may not have been nearly as pronounced as had commonly been assumed. Considering that second- and third-generation MVs tended to mature much more rapidly than the original MVs, average yield per day may not have declined at all. Based on their analysis of TFP trends, Mohan Dey and Evenson concluded that during the period of analysis, modest productivity gains averaging slightly less than 1% per year were achieved in both rice and wheat. Decomposition of the TFP index suggested that the productivity gains were attributable in large part to research investments.

Partial factor productivity (PFP) studies — Unlike TFP indices, which relate changes in output to changes in the use of all inputs, partial factor productivity (PFP) indices relate changes in output to changes in the use of individual inputs. Indices of PFP have advantages and disadvantages: they can provide useful information about the efficiency with which individual inputs are used, but they may not provide an accurate view of trends in overall productivity, because a change in the productivity of one factor is frequently accompanied by offsetting changes in the productivity of other factors.

Byerlee and Siddiq (1994) disaggregated the effect of three factors on irrigated wheat yields in the Punjab of Pakistan: (1) initial adoption of MVs, (2) replacement of old MVs with newer MVs, and (3) increasing fertilizer application levels. After the (positive) effects of these three factors had been accounted for, wheat yield trends showed a significant negative residual, suggesting that other factors were responsible for a long-term decline in yields (and hence productivity). This conclusion is supported by observed trends in yields of wheat MVs, which have remained unchanged during the past two decades despite extensive adoption of MVs, replacement of old wheat MVs by new MVs, and significant increases in the amount of fertilizer applied to wheat.

Kumar and Rosegrant (1994) similarly disaggregated productivity trends for rice in India from 1971/72 to 1988/89. For the country as a whole, productivity growth averaged 1.0% over the entire period of analysis, with market infrastructure, research investment, the availability of canal irrigation, and balanced use of fertilizers representing the most important sources of productivity growth. However, productivity trends were found to vary considerably between regions (Table 8). Productivity growth was reported to be strong in the southern region and modest in the northern and eastern regions, but in the western region productivity declined by an alarming 1.0% per year. Productivity growth in rice also was found to have declined over time, with average annual increases smaller during the post-Green Revolution period (1981-88) than during the Green Revolution period (1971-80).

Table 8. Trends in input, output, and total factor productivity for rice in India, 1971/72 to 1988/89

	Total input	Total output	Total factor productivity
Region			
Eastern	1.81*	2.17*	0.36**
Western	1.74**	0.76	- 0.98
Northern	6.03*	6.79*	0.76*
Southern	1.12*	2.97*	1.85*
All India (excluding Western Region):			
1971-80	2.99*	4.30*	1.31*
1981-88	2.13*	3.10*	0.97*
1971-88	2.49*	3.52*	1.03*

Source: Kumar and Rosegrant (1994).
Note: *,** indicate significance at the 5% and 1% level, respectively. Eastern Region comprises Assam, Bihar, Orissa, West Bengal; Western Region comprises Gujarat, Maharashtra, Madhya Pradesh, Rajasthan; Northern Region comprises Punjab, Haryana, Uttar Pradesh; and Southern Region comprises Andhra Pradesh, Tamil Nadu, Karnataka, Kerala.

Micro-level evidence: long-term experiment station data — Despite methodological inconsistencies that complicate the comparison of empirical results, the factor productivity studies suggest that it may be dangerous to look at rising yields and conclude that all is well in South Asia's rice-wheat cropping systems. Since the onset of the Green Revolution, average rice and wheat yields have indeed increased throughout the region. However, we now know that yield gains in farmers' fields have been achieved only through the application of ever-increasing amounts of inputs. When changes in the quantity and quality of inputs are taken into account, the picture changes: yields frequently not only stagnate, but in some cases they actually decline.

Why has this development not been recognized more widely by researchers? One reason is that researchers may not have been looking in the right places. Most rice and wheat research in South Asia has tended to focus on the development of technologies designed to increase productivity in the short run, generally one or two cropping cycles. Long-term trials — including monitoring trials designed to track developments in farmers' fields — have been seen as time-consuming and costly, so they have rarely been undertaken. Only recently has the emerging realization that potentially important long-term processes are being overlooked induced some researchers to extend the time frame of their analyses in an attempt to identify and understand factors that may be affecting productivity over the longer term.

In the wake of this shift in perspective, evidence of long-term productivity declines is beginning to show up at the experimental level. A number of soil fertility trials have examined the behavior of rice and wheat yields over the long run in continuous rice-wheat cropping systems. These trials have generally examined the effects of different combinations of fertilizer. Although most research has focused on the effects of major nutrients (N, P, K), some trials have included treatments with organic fertilizers, and a few have even considered the effects of micronutrients, such as zinc, sulfur, and boron. Few of these long term-trials have been properly analyzed and written up, but even partial results provide valuable insights into the long-term behavior of rice and wheat yields in rice-wheat cropping systems.

Researchers in Nepal are conducting a set of trials designed to shed light on the long-term performance of rice and wheat yields under intensive two- and three-crop rotations (Giri, Acharya, and Regmi 1994). Data from rice-rice-wheat trials planted at the Bhairahawa research station show that in plots treated with recommended applications of nitrogen (N), phosphorus (P), and potassium (K) fertilizer, yields of both rice crops (planted early and planted on time) clearly have declined; yields of wheat may also have fallen slightly, although the rate of decline is not statistically significant (Table 9). In plots treated with farm yard manure (FYM), declining yields have been observed in all three crops. Since application of FYM has increased the organic matter content of the soils and improved their nutrient status compared to the plots treated only with chemical fertilizer, factors other than soil fertility *per se* appear to be limiting yields. When phosphorus is omitted from the treatment, yields decline even more rapidly.

Also in Nepal, yield declines in wheat have been observed in varietal trials conducted at six research stations in the lowland *Terai* (Morris, Dubin, and Pokhrel 1994). Between 1976 and 1990, yields of the check variety RR21 declined at an average annual rate of 6.8%, while yields of the variety UP-262 declined more slowly at a rate of 4.3% (Figure 15). During the course of the trial, RR21 became susceptible to leaf rust and blight, and the difference in the rate of yield decline experienced by the two varieties (2.5 %) can be attributed to disease effects.

Table 9. Trends in rice and wheat yields, long-term trials, Bhairahawa, Nepal, 1976-90 (average annual percentage change)

	Treatment		
	N-P-K 100-30-30	FYM	N-P-K 100-0-30
Rice planted on time[a]	-4.51**	-7.75**	-27.92**
Rice planted early[a]	-10.15**	-7.74**	na
Wheat planted on time	-0.99	-2.56*	-11.90**

Source: Calculated by the authors from data reported in Giri, Acharya, and Regmi (1994).
Note: *,** indicate significance at the 5% and 1% level, respectively.
[a] Rice yields adjusted to account for varietal change occurring in 1987.

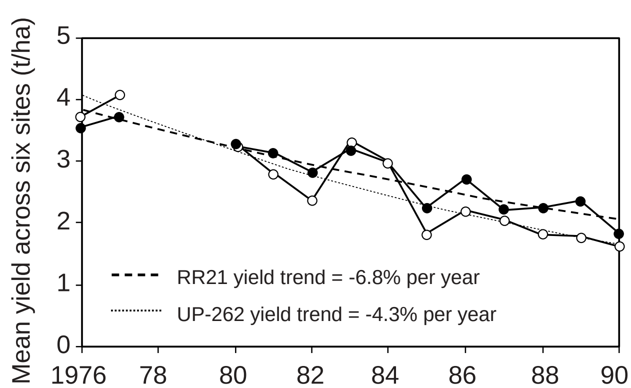


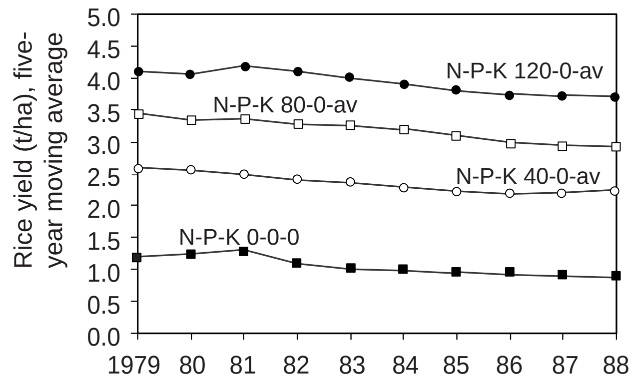
Figure 15. Mean yields of RR21 and UP-262 in the Terai, Nepal, 1976-90.
Source: Morris, Dubin, and Pokhrel (1994).

However, the fact that both varieties experienced significant declines in yield despite constant levels of management suggests that soil fertility or other as yet unidentified factors were depressing yields.

Trials designed to measure the long-term behavior of rice and wheat yields under continuous multiple cropping also are underway in India. Experiments at Pantnagar, Uttar Pradesh, show declining yields in intensive rice-wheat systems when input levels are kept constant (Figure 16) (Nambiar 1994). Yield declines in intensive rice-wheat systems have also been recorded in Faizabad, Uttar Pradesh, although there is evidence of an eventual leveling off of yields (Figures 17a, 17b).

The results of the Faizabad experiment are particularly interesting, because they provide clear evidence of long-term degradation in the natural resource base. In Faizabad, yield declines have occurred across a wide range of fertilizer application rates, suggesting that there has been a downward shift in the entire fertilizer response function. Such a shift is illustrated in Figure 18. As a result of resource degradation, the yield level achieved at fertilizer application rate X_0 has declined from Y_0 to Y_1. Only by increasing fertilizer application rate to X_1 can the original yield level Y_0 be maintained. Because the entire response production function has shifted down, this effect is evident at all levels of fertilizer application.

17a. Rice yields in long-term trials



17b. Wheat yields in long-term trials

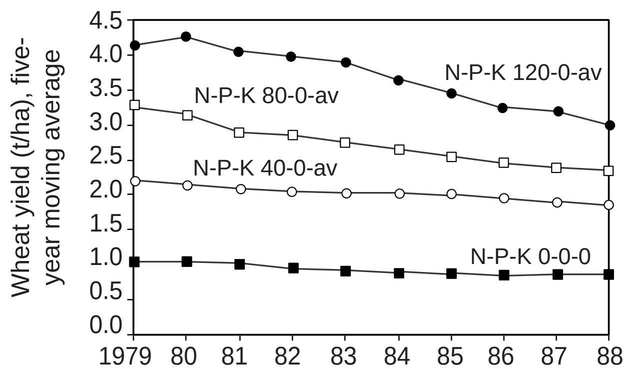


Figure 17. Rice and wheat yield trends, long-term trials, Faizabad, U.P., India, 1979-88.
Source: Woodhead (n.d.).

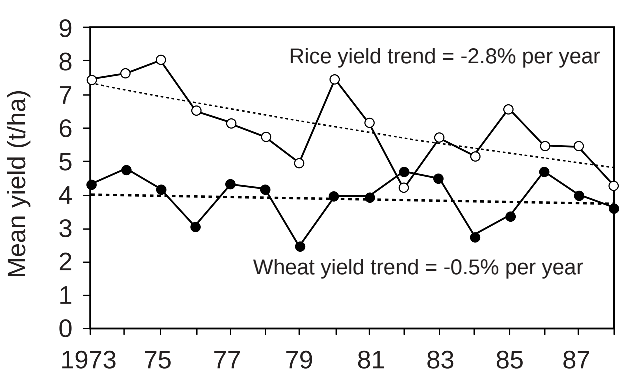


Figure 16. Rice and wheat yields, long-term trials, Pantnagar, U.P., India, 1973-88.
Source: Nambiar (1994).

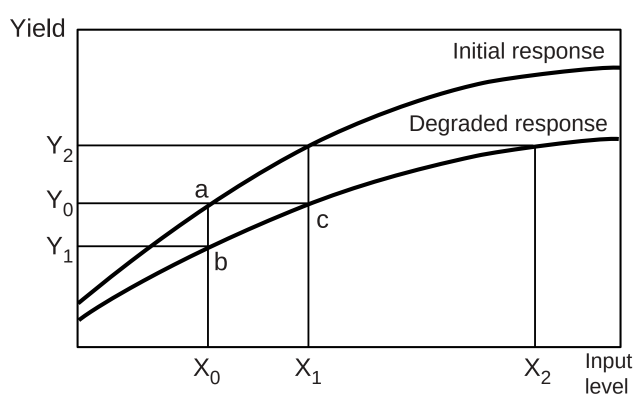


Figure 18. Shift in fertilizer response function resulting from resource degradation.
Source: Byerlee (1987).

Elsewhere in Asia, signs of long-term yield declines in intensive cereal cropping systems have emerged in work involving continuously cultivated rice systems. Since this work involves different cropping patterns and different management practices than those typically found in the rice-wheat belt, the results cannot be considered directly applicable to rice-wheat systems.[23] Nonetheless, they highlight how intensive cropping systems over time can begin to show signs of degradation. Flinn and De Datta (1984), Cassman et al. (1995), and Cassman and Pingali (1995) all report a downward shift in the nitrogen response curve, which they attribute to a decline in the ability of the soil to release native nitrogen for crop growth. Pagiola (1995) describes declines in *boro* rice yields recorded by researchers from the Bangladesh Rice Research Institute in long-term, multiple-crop trials, even when recommended levels of nutrients were applied. Similar factors may be contributing to the declines in input response observed in rice-wheat systems.

Although these and other long-term trials provide evidence of yield declines in continuously cultivated rice-wheat systems, it is not always easy to determine if declining yields are due to soil fertility problems. The law of diminishing returns suggests that the rate of fertilizer application should be inversely related to the productivity of fertilizer, but the evidence on this issue is surprisingly inconclusive. One easily calculated measure of average fertilizer-use efficiency, the ratio of grain weight to nitrogen weight, appears to indicate that fertilizer productivity has indeed declined. In India this ratio for rice fell from about 60 in 1966 to less than 10 in 1992; during the same period, the ratio for wheat fell from about 15 to around 5 (Figure 19).

But the ratio of grain weight to nitrogen weight is deceptive, because it assumes that yields would be zero if no fertilizer were applied (which obviously is not the case). More sophisticated measures of average fertilizer-use efficiency, such as the ratio of marginal grain weight to fertilizer weight (marginal grain weight is the grain weight above some base yield achieved without fertilizer), suggest that fertilizer productivity declines may not have been as extensive as is widely assumed. In the Indian state of Haryana, for rice the ratio of marginal grain weight to fertilizer weight has fallen since the mid-1970s, but for wheat the ratio has increased slightly (Figure 20). Other measures of marginal fertilizer-use efficiency similarly fail to establish whether or not fertilizer productivity has declined in rice-wheat systems. Chaudhary and Harrington (1993) divided changes in crop yields by changes in fertilizer use rates to measure factor

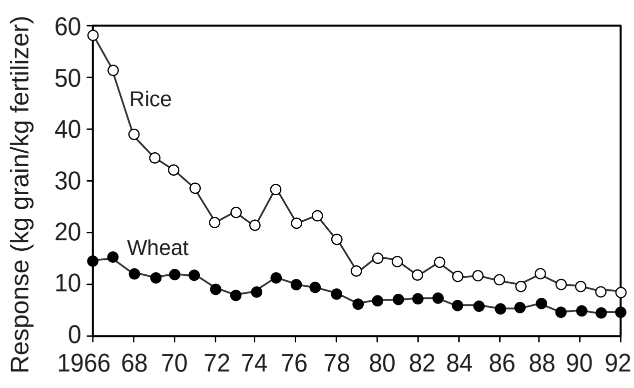


Figure 19. Average response of rice and wheat to fertilizer, all India, 1966-92.
Source: Fertiliser Association of India (various years).

[23] In continuously cultivated rice cropping systems, soils are kept wet for most of the year; because soils are kept permanently in a reduced condition, they tend to differ from rice-wheat soils, which are periodically dried and oxidized.

productivity trends in Haryana during the 1970s and 1980s. They found that fertilizer productivity declined for rice, but it increased for wheat — indicating that diminishing returns associated with increased use of fertilizer may have been offset (and in the case of wheat overpowered) by farmers' adoption of improved germplasm and crop management practices.[24]

Sustainability Issues in Rice-Wheat Cropping Systems

If the rate of productivity declines in rice-wheat cropping systems remains uncertain, the causes of productivity declines are even less well understood. Many "explanations" have been put forward, most of them only weakly supported by empirical evidence, and therefore they must be regarded as unconfirmed hypotheses. What has become clear is that the causes of apparent declines in productivity are often site specific, varying from one location and one cropping system to another.

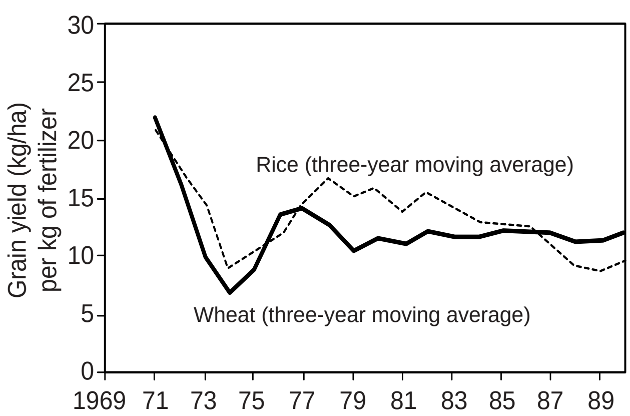


Figure 20. Marginal response of rice and wheat to fertilizer, Karnal, India, 1969-90.
Source: Chaudhary and Harrington (1994).

Soil problems

Soil problems (involving chemical, physical, or biological factors) are obvious candidates to blame for long-term productivity declines. Because most rice-wheat cropping systems are heavy extractors of nutrients, chemical deficiencies are bound to develop after years of continuous cropping unless steps are taken to restore fertility levels. Although this conclusion seems inescapable, it has been remarkably difficult to establish clear links between soil fertility levels and productivity declines in rice and wheat. Deficiencies of nitrogen and phosphorus are known to cause yield losses, but most farmers now apply these two elements at close to recommended levels. Potassium, which is less commonly applied, may be causing problems in some areas, although often it has been ruled out as a cause of yield declines. Micronutrients such as zinc, boron, and manganese are often suggested as yield-limiting factors, but trials that include these elements rarely generate conclusive evidence to corroborate this hypothesis. Organic matter levels also are known to affect soil chemistry, yet the role of organic matter in rice-wheat cropping systems is imperfectly understood. Field surveys make clear that farmers are applying less manure to their rice and wheat plots (primarily because of its increasing value for use as cooking fuel), but empirical evidence linking the decreased use of manure to specific nutrient imbalances in rice-wheat cropping systems is lacking.

Soil physical factors also can affect the productivity of rice-wheat systems. The puddling of rice soils leads to the breakdown of soil aggregates, resulting in reduced pore sizes and the formation in some soils of a plow pan.

[24] Elsewhere in Asia, evidence is emerging that marginal returns to fertilizer use on rice also are decreasing rapidly in intensively cultivated rice-rice systems (for example, see Cassman and Pingali, 1994).

Puddling restricts water movement and affects soil reactions in ways that are favorable for rice but unfavorable for wheat. Puddling may be one of the major causes for reduced wheat yields when wheat follows rice, especially in fine-textured soils. Linked to the problem of puddling is that of poor rooting. Few studies have been conducted on rooting processes in rice-wheat systems, except in the coarse soils of the Indian Punjab (Gajri, Arora, and Prihar, 1992). Poor rooting of wheat following rice (because of poor soil structure, waterlogging, and root-restricting soil layers) may be a major cause of declining productivity in wheat and should be included in the future research agenda.

Soil biological factors have received relatively little attention from researchers but may also be contributing to productivity declines in rice and wheat. Solarization trials conducted at the Bhairahawa station in Nepal show that the incidence of root nematode in rice and root necrosis in wheat are negatively correlated with yield, indicating that underground pathogens may be partly responsible for reducing yields (Dubin and Bimb 1994). In the Philippines, Cassman and Pingali (1995) hypothesize that the main cause of declining rice yields has been a reduction in the soil's natural ability to provide nitrogen, which they attribute to interactions between organic matter and soil microbes. Although Cassman's and Pingali's conclusions were based on experimental work involving rice-rice systems, similar processes could be at work in rice-wheat systems.

Water problems

Expansion in irrigated area and intensification of cropping patterns have increased the demand for irrigation water throughout South Asia. In many areas, use of water to irrigate rice and wheat has surpassed the natural ability of the ecosystem to replenish itself. At the same time, increased demand for irrigation water has adversely affected the quality of water, with additional negative effects on productivity. Problems relating to the quantity and quality of water have already impaired productivity in many areas and threaten to become even more of a limiting factor as more and more water is diverted to non-agricultural uses.

Concern over water availability has mounted especially fast in northwestern India (Maklin and Rao 1991; Malik and Faeth 1993; Pandey, Dwivedi, and Sharma 1992). During the past decade, water tables have dropped at a rate of 0.5-0.8 m per year in the state of Haryana (Harrington et al. 1993) and at a rate of 0.2-1.0 m per year in the neighboring state of Punjab (Gill 1992, 1994). Declining water tables not only raise production costs (by forcing farmers to pump water from greater depths), but such rapid rates of decline raise serious questions about the long-term sustainability of rice-wheat systems. In some areas, farmers are already being forced to cut back on the number of irrigations they can apply to their rice and wheat crops, and where water shortages are particularly acute, they are sometimes forced to limit plantings.

Problems relating to the quality of irrigation water have also multiplied. Many rice-wheat tracts in northeastern Pakistan and northwestern India are being affected by water-borne compounds. Tubewell water in particular can contain salts and minerals that over time reduce the productivity of soils. Data generated at the Soil Fertility Institute in Lahore, Pakistan, show that wheat yields are often lower in plots irrigated by tubewell than in plots irrigated using canal water (Figures 21a, 21b). Although researchers still lack conclusive proof, they suspect that tubewell water contains salt concentrations which over the long term affect soil productivity. This hypothesis is supported by data from other studies showing that tubewell water in the Pakistani Punjab contains high levels of salts (Kijne and Vander Velde 1990, Byerlee and Siddiq 1994). Salinity and sodicity problems are sometimes exacerbated by poor water management practices in the lower reaches of canal irrigation systems, where sufficient water may not be available to leach out salts (Kijne and Vander Velde 1990).

Weed, insect, and disease problems

Agricultural intensification in general and continuous cropping of cereals in particular have increased the incidence of weed, insect, and disease problems in some rice-wheat zones. Among the many weeds that negatively affect productivity, the most damaging is *Phalaris minor*, a grassy weed which poses an especially serious problem for wheat, especially in cooler areas (rice is not affected by *Phalaris*). Long present in South Asia as a minor weed, *Phalaris* has become a major problem in recent years, particularly in continuous rice-wheat cropping systems. If left unchecked, *Phalaris* can cause crop losses in wheat of nearly 100% (Aslam et al. 1989, Harrington et al. 1993, and Hobbs et al. 1991, 1992). Chemical control must be used, since weeding by hand is ineffective. Although chemical control has proved effective thus far, evidence is now emerging that *Phalaris* is developing resistance to isoproturon, the most extensively used herbicide in India (Malik and Singh 1993).

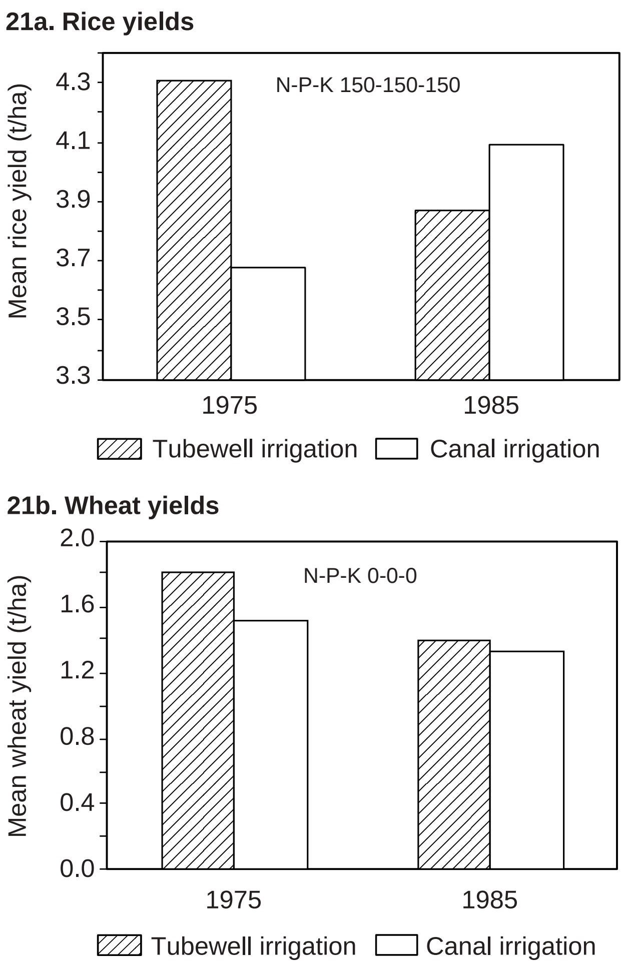


Figure 21. Rice and wheat yields by irrigation source, Lahore, Pakistan, 1975 and 1985.
Source: Kijne and Vander Velde (1990).

Continuous rice-wheat cropping has been accompanied in some areas by an increase in insect pest problems. Growth in the area planted to rice and wheat has expanded the host environment for many insects, while intensification of the cropping pattern has extended the period during which the host environment is present. The result has been a noticeable buildup in insect populations and the appearance of overlapping generations of insects within the same cropping season. With the exception of localized outbreaks, insect problems remain relatively minor (although damage caused by the rice stem borer can be extensive). However, insect problems are likely to proliferate in the future as the result of additional expansion in rice-wheat area, further intensification of rice-wheat systems, and the increasing domination of a relatively small number of popular MVs.

Continuous rice-wheat cropping also improves conditions for the buildup of many plant diseases, especially leaf diseases in rice and

Karnal bunt and foliar blights in wheat. Contrary to the conventional wisdom, most MVs carry high levels of resistance to major diseases — higher levels, in many cases, than were present in the old TVs they replaced. Yet despite the higher levels of resistance, diseases remain a threat if the enhanced resistance is offset by a lack of varietal diversification in farmers' fields. Farmers within localized zones sometimes all decide to grow the same MV — usually the MV which yields the highest within that zone. Under these circumstances, if the resistance of a particularly popular MV breaks down, a large area may be affected.

Crop management problems

Productivity levels in rice-wheat cropping systems have been negatively affected by the intensification process itself, in the sense that management decisions taken to increase the productivity of one crop often have negative consequences for the productivity of other crops in the rotation. For example, farmers who decide to increase rice production by switching to a longer-duration rice variety frequently must delay planting their wheat crop following the rice harvest (Byerlee and Husain 1992). Delayed planting of wheat significantly reduces potential yields and decreases the efficiency of fertilizer uptake (Hobbs 1985, Saunders 1990). Adoption of reduced tillage practices can help to alleviate this problem, but introduction of reduced tillage technology in turn is likely to create new problems (e.g., stem borer carryover in unplowed rice stubble) (Aslam et al. 1989, Majid et al. 1988). Another example of the crop management problems that can arise in rice-wheat rotations involves the different land preparation requirements of the two crops, with puddling being beneficial for rice but harmful for wheat.

Challenges for Research and Research Organization

Technical change: Past, present, and future

Byerlee (1992) has described a sequential process of technical change which is helpful in thinking about the agricultural intensification currently taking place in South Asia's rice-wheat cropping systems. According to Byerlee, technical change in Asian agriculture proceeds through three stages, distinguished by the development and diffusion of technologies to substitute for emerging factor scarcities:

- a *Green Revolution Phase,* during which MVs first become available and, when grown with modest levels of purchased inputs, lead to a surge in productivity;
- a *First Post-Green Revolution Phase* (*Input Intensification Phase*), when farmers improve allocative efficiency by increasing the level of use of purchased inputs, resulting in movement toward economically optimal use of these inputs; and
- a *Second Post-Green Revolution Phase* (*Input Efficiency Phase*), during which farmers move toward increased technical efficiency by using available purchased inputs more efficiently while adopting practices that contribute to the sustainability of the resource base.

These stylized stages of technical change can be depicted diagramatically (Figure 22). During the Green Revolution Phase, the introduction of MVs shifts the production function upwards (TV to MV_1), increasing crop response to complementary inputs such as fertilizer and water and leading to a one-off surge in productivity (A to B). Adoption of modest levels of these complementary inputs accompanies adoption of MVs, although farmers for some time fail to exploit the full benefits of the new technology and continue to operate well below the technological frontier. During the First Post-Green Revolution Phase, farmers become familiar with the technology and move along the (suboptimal) production function (B to C), using higher levels of complementary inputs to improve the allocative efficiency of production. Finally, during the Second Post-Green Revolution Phase, farmers approach the new production frontier (MV_2) by further increasing the efficiency with which they use inputs. Depending on the strategy followed by farmers, use of complementary inputs may increase (D) or decrease (E) during this phase.

The three phases described by Byerlee are useful in thinking about the intensification of South Asia's rice-wheat cropping systems because they provide important insights into how the products and information needed from the agricultural research system have changed over the years and how they will continue to change.

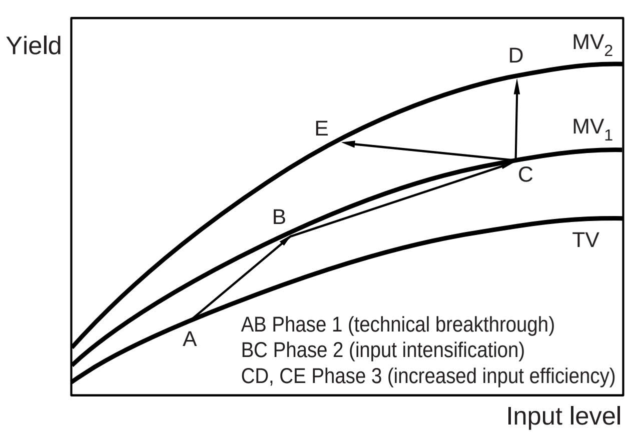


Figure 22. Phases of technical change (following Byerlee).
Source: Byerlee (1992).

During the Green Revolution Phase, production technologies are largely input-based, and the role of the research system need not extend much beyond developing innovations that can be extended to farmers in blanket fashion. This was indeed the experience throughout many of the areas in South Asia where the Green Revolution technologies had their initial dramatic impact. Modern varieties, fertilizer, and irrigation technologies were transferred to farmers via standardized technical packages, which came with generic management recommendations developed largely on research stations.

During the First Post-Green Revolution Phase, seeds, fertilizer, and water (irrigation) still have the capacity to deliver productivity gains, but the management of these key inputs must be fine-tuned. This second developmental stage described by Byerlee also was borne out in the evolution of South Asia's rice-wheat cropping systems. As MVs spread out of the relatively homogeneous irrigated tracts of northwestern India and northeastern Pakistan into less favorable production zones, local crop management research was needed to adapt the original blanket recommendations to specialized conditions. In addition, after the first generation of MVs had spread throughout the region's irrigated zones, local crop breeding efforts were needed to adapt imported varieties to distinct niches determined by agroclimatic conditions and cropping patterns. Local breeding was also instrumental for carrying out maintenance breeding to preserve host-plant resistance to mutating insect pests and diseases.

During the Second Post-Green Revolution Phase, new approaches to research are required to develop the sophisticated, site-specific management information needed to improve input-use efficiency in the context of increasingly complex cropping systems where avenues for successful change are limited. This third and final stage described by Byerlee is already evident in the more intensively cultivated areas of the central rice-wheat belt, where multidisciplinary, systems-oriented teams of researchers are working with farmers to explore innovative crop management technologies designed to boost productivity by simultaneously attacking problems from several different angles. Because this research requires input from many different disciplines, as well as constant interaction from farmers through diagnostic surveys and on-farm testing, it tends to be costly to implement and difficult to manage.

Organization of agricultural research in South Asia

The fact that different technologies and different types of information are needed at different stages in the intensification process has important implications for the organization and management of agricultural research. It is useful to review the recent history of research to see whether technology development efforts are evolving to keep pace with the changing needs of farmers.

The initial success of Green Revolution technologies had a profound influence on the organization of agricultural research in South Asia. Impressed by the rapid spread of MVs and by their catalytic effect on use of fertilizer and irrigation, research managers throughout the region moved quickly to adopt the commodity-based strategy followed by the international agricultural research centers (IARCs).[25] During the late 1960s and early 1970s, rice and wheat research programs were formed in virtually every country of South Asia. As in IARCs, highest priority was assigned to germplasm improvement; the primary goal was to develop new and better MVs. In addition to plant breeders, the institutes typically included plant pathologists, physiologists, entomologists, and agronomists, all of whom directly or indirectly supported breeding activities. Even crop management research was intended to support germplasm improvement; agronomists were assigned responsibility for determining the planting dates, seeding rates, fertilizer application rates, irrigation practices, and weed control practices that would enable MVs to perform up to their potential.

Many of the specialized rice and wheat research programs were successful. Although frequently hampered by inadequate funding and shortages of trained staff, they managed to develop a considerable amount of improved germplasm. Following an initial start-up period, locally developed modern rice and wheat varieties began to appear in the mid-1970s. In subsequent years, the rate of releases increased as national breeding programs grew in strength, and by the mid-1980s the regions' stronger programs (e.g., India, Pakistan) were releasing rice and wheat varieties at an impressive rate (Dalrymple 1986a, 1986b; Byerlee and Moya 1993). This work by national research programs was actively supported by the IARCs, primarily through provision of improved germplasm and through training of scientific personnel.

The commodity-based strategy was particularly effective during the Green Revolution period, when MVs of rice and wheat were still spreading into new areas. Although the MVs that had originally

[25] In India, commodity-oriented research programs predated the formation of the IARCs, so the success of the Green Revolution merely served to accelerate an ongoing trend.

spearheaded the Green Revolution proved to be well adapted to irrigated zones, they were not always suitable for marginal production environments. Additional breeding research was therefore needed to adapt improved materials to local requirements. National rice and wheat research institutes organized around a strong core of plant breeding activities proved effective at accomplishing this task.

However, circumstances have changed. Productivity growth is slowing, suggesting that the easy gains from the original Green Revolution technologies have for the most part been realized. Throughout large parts of South Asia's rice-wheat belt — particularly the irrigated parts — adoption of MVs is now virtually complete, fertilizer application rates are approaching optimal levels, and the potential for affordable irrigation is largely exhausted. By implication, if growth in food production is to keep pace with projected increases in demand, new sources of productivity growth will have to be tapped.

Where will future productivity gains come from? Traditional sources of productivity growth will continue to be important. Germplasm improvement (involving conventional plant breeding methods and/or emerging biotechnology techniques) no doubt will be instrumental in further increasing the yield potential of rice and wheat. Hence the current strong interest in developing commercially viable hybridization technologies, in altering the architecture of rice and wheat plants to increase their ability to bear grain, and in developing transgenic species incorporating genes conferring resistance to important diseases and insect pests.[26] But germplasm improvement work alone probably will not be enough to carry the day. Although future gains from plant breeding are likely to be significant, it probably will not be possible to repeat the progress achieved during the past 30 years. For this reason, it seems likely that future growth in productivity in South Asia's rice-wheat cropping systems will come increasingly from adoption of improved management practices designed to increase the efficiency of input use and/or to arrest (or reverse) the degradation of soil and water resources (Byerlee and Pingali 1995). In other words, information and knowledge, rather than simply inputs, will become increasingly important.

Weaknesses of current approaches to research

The shift in emphasis from input-based technologies to knowledge-based technologies suggests that changes will be needed in the organization of research. Most research organizations, both national and international, are still organized along lines that reflect the needs of an earlier period. Scientists continue to place inordinate emphasis on controlled experimentation designed to develop packages of recommendations for distribution to farmers. Meanwhile, insufficient attention is being paid to understanding the increasingly complex problems that threaten to undermine the sustainability of rice-wheat cropping systems and to designing flexible solutions that farmers can adjust to their own particular circumstances.

This idea is hardly original. A few far-sighted research administrators long ago realized that research based on experiment stations and organized along strict commodity lines cannot effectively address the complex problems which

[26] The productivity gains from germplasm improvement work have by no means been exhausted. For example, the so-called "super rices" currently being developed at IRRI are expected to deliver yield gains of 12-15% compared to the best commercial varieties.

are bound to arise in the post-Green Revolution period. For years, these visionaries have argued that more effective interdisciplinary collaboration between researchers and closer links with farmers will be needed if increasingly complex problems are to be diagnosed properly and solved. In several South Asian countries, advocates of these views were sufficiently influential to bring about the establishment of systems-oriented research programs, usually in the form of cropping systems/farming systems units lodged within the commodity-based institutes. However, these units generally failed to make a noticeable impact (Tripp 1991). Their lack of success can be attributed to several factors:

- Cropping systems/farming systems divisions often were formed as independent units staffed by scientists seconded from established disciplinary departments. Threatened by a loss of personnel and operating funds, managers of the established departments sometimes attempted to impede the transfer of resources. Cropping systems/ farming systems divisions thus found themselves isolated from the rest of the research system and denied access to much-needed technical and financial support.

- Incentives to link commodity-oriented research institutes through collaborative projects were usually lacking. Every institute maintained a separate agenda, and many chose to establish their own farming systems units. Expertise needed to unravel problems related to the productivity of the overall farming system may have existed in other institutes, but for all intents and purposes it was unavailable.

- Individual scientists tended to avoid involvement in systems-oriented research because such work was rarely given adequate recognition. Professional advancement was generally tied to achievements in more strategic research areas (that is, in theoretical or methodological research). Applied problem-solving research such as that envisioned for farming systems teams was considered less prestigious.

- Interdisciplinary research units rarely had strong links to the extension service, making propagation of research results difficult. It did not help that the extension services often faced full agendas of their own and rarely had incentives to collaborate with researchers.

- Systems-oriented research was supposed to involve farmers, but in many instances farmers were not actively consulted during the planning, testing, and evaluation of new technologies.

Elements needed for future research to be effective

South Asia's agricultural research programs today stand at a crossroads. Established during an earlier era when funding was plentiful, most of the region's research institutes have been slow to adapt to the fiscal austerity of the 1990s. Even as the research agenda has grown and broadened, raising new and increasingly complex technical challenges, research administrators have failed to take the necessary steps to improve priority-setting, streamline operations, increase accountability, and motivate staff. At the same time, they have failed to develop the base of political support needed to ensure continuing funding for research (Byerlee and Pingali 1995).

If reform of the organization and management of research is overdue, what would a re-engineered research system look like? Without trying precisely to describe an "ideal" system (which would in any case be impossible, since institutional requirements differ between countries), it should be possible to describe some of its salient characteristics.

1) **Expanded focus —** Research programs should continue conducting problem-focused "downstream" research designed to increase the efficiency of farmers' resource use in the short run, but this kind of traditional, applied research will have to be complemented by more strategic "upstream" research designed to shed light on factors affecting the long-run productivity of major cropping systems (e.g., processes contributing to resource degradation). Added emphasis must be given in particular to diagnostic research aimed at identifying problems that constrain growth in productivity; describing the pace, incidence, and severity of these problems; unraveling their causes; and predicting their consequences. If this is to be accomplished, more effort will have to be invested in monitoring what goes on in farmers' fields, both in terms of cropping practices and in terms of changes in the natural resource base upon which agriculture depends.

2) **Farmer participation —** Far too many scientists in South Asia spend most of their time on the research station, rarely venturing forth to observe what is happening in farmers' fields or to solicit direct feedback from farmers. Researchers need increased input from farmers for a more accurate diagnosis of problems and more effective design of potential solutions. Once problems have been correctly identified and alternative prototype solutions proposed, farmer participatory adaptive research can help to tailor the solutions to specific farming systems and farmer circumstances. Strengthening links to farmers thus will speed the adaptation of new technologies to local conditions, leading to more rapid and possibly more complete adoption.

3) **Multidisciplinary perspective —** Collaboration among disciplines must begin at the diagnosis stage and extend to research planning, implementation, and evaluation. Individual scientists can assume responsibility for separate components of a research project (which is often desirable to take advantage of disciplinary expertise), but results must be discussed and evaluated with colleagues from other disciplines. Achieving effective multidisciplinary collaboration will require significant changes in the structure of the professional incentive system, which at present disproportionally rewards disciplinary work of a more theoretical nature, as opposed to multidisciplinary work which is more problem-solving in nature.

4) **Intercommodity alliances —** As cropping systems continue to intensify, intercommodity alliances will become increasingly important in the research system. We now know that farmers in the rice-wheat belt take decisions based on a sophisticated understanding of the productivity of their entire household economy (including both agricultural and non-agricultural activities). Gone are the days when researchers could investigate production technologies affecting one crop without regard to the implications of these technologies for other crops in the system, for livestock, and even for non-agricultural activities.

5) **Improved links between researchers and extension specialists —** As crop management practices become ever more complex, additional effort will be needed to ensure that effective mechanisms exist to speed the flow of technology from researchers to extension specialists to farmers, as well as the opposite flow of information about farmers' technology needs and about the performance of new technologies in farmers' fields. At present, researchers and extension specialists often work in virtual isolation from one another. Researchers must come to understand that their responsibility extends beyond the development of new technologies and that they have a duty to participate actively in the technology transfer process, a reality that must be reflected in the structure of professional incentives and rewards. At the same time, extension agents must be encouraged to serve as a two-way conduit capable of effectively conveying information in both directions between researchers and farmers.

6) **Regional and international collaboration —** Regional and international collaboration is needed to facilitate the exchange of ideas, eliminate redundant research, and increase efficiency. Recent work has shown that technological spillovers between countries and/or between regions within countries are often extensive, particularly in the case of plant breeding research (Byerlee 1995, Maredia and Byerlee 1996). Given that research activities currently tend to be distributed among a large number of state or district research institutes, this suggests that considerable cost savings could be achieved by concentrating research efforts within a relatively small number of adequately staffed and well-equipped institutes.

An example of the gains that can be achieved through regional and international collaboration is provided by the Rice-Wheat Consortium (RWC), a partnership linking four public national agricultural research systems (NARSs) and five IARCs which share the goal of increasing productivity in South Asia's rice-wheat cropping systems. Collectively managed by means of a joint Steering Committee, the RWC is working to improve the efficiency of rice and wheat research by coordinating the activities of consortium members. Representatives from RWC member organizations convene regularly to identify and prioritize important research problems and to devise collective strategies for their solution. Responsibility for specific topics is assigned to the institution or institutions best equipped to address them, the idea being to exploit each institution's comparative advantage while avoiding wasteful duplication of effort. In addition to coordinating the design of research, the RWC serves as an effective mechanism for speeding the dissemination of relevant research results via conferences, publications, and consultations.

Within the RWC, teams of researchers are concentrating on several themes which are illustrative of the "third-phase" problems described by Byerlee. For example, one team is working to develop innovative methods of land preparation-cum-stand establishment designed simultaneously to reduce tillage costs, improve soil structure and fertility, facilitate stand establishment, and speed turnaround between crops (e.g., minimum or reduced tillage, surface seeding of wheat, and direct sowing of rice). Another team of researchers is exploring integrated pest management (IPM) strategies designed to reduce pest-induced crop losses through use of resistant varieties, judicious management of rotations, elimination of pest habitat, and limited application of chemical pesticides. A third team is working to develop water management practices designed to increase water-use efficiency, to moderate or reverse chemical imbalances caused by water use (e.g., salinity, sodicity), and to lower irrigation costs. Other research themes addressed by the RWC include soil fertility management, disease management, and weed management.

One important lesson emerging from the RWC's activities is that research on complex "third-phase" problems requires new and innovative approaches to research planning. As more and more demands are placed on the pool of funds available for research, national funding agencies and international donors are becoming increasingly reluctant to provide "open checkbook" support for diversified, multicomponent, long-term research programs. Instead, they tend to favor clearly focused, limited-duration projects that can be easily monitored and whose outputs are readily defined. Given this change in the funding environment, research planning is necessarily becoming more costly and more time-consuming. With research issues growing increasingly complex, considerable effort is now required to ensure that individual research projects designed to focus on a specific problem area (e.g., "direct seeding of wheat using mechanical seed drills") remain appropriately articulated within a larger research theme (e.g., "improved crop establishment technologies for wheat following rice"). Effective management of research teams is becoming more important, given the need to ensure that all relevant disciplines are appropriately represented and that individual responsibilities of participating researchers are well defined and clearly understood. Parenthetically, it should be noted that the management function, which requires time and effort, must be recognized and appropriately rewarded in the allocation of research funds.

Conclusions

The rice-wheat systems of South Asia enjoy a well-deserved reputation of being among the most productive cropping systems in the world. Thanks to the wealth of their natural resources, the industriousness of their inhabitants, and the effectiveness of modern crop production technologies, they have played a vital role in helping to avert the massive food shortages that many observers were predicting as recently as 20 years ago. But while the remarkable success achieved in feeding an exponentially increasing population provides grounds for optimism about the future of agriculture in South Asia, the achievements of the past should not generate a false sense of security. As this paper has tried to show, troubling signs are beginning to emerge that the successes of the past will be difficult to duplicate and that it may be difficult even to sustain current levels of productivity unless steps are taken soon to safeguard tomorrow's food supplies.

Farmers in South Asia have asserted for some time that the productivity of rice-wheat cropping systems is declining, but researchers and policy makers have been slow to pay them heed. To this day, many people (including many agricultural specialists) deny that a problem even exists. Their complacency is perhaps understandable, because the warning signs are not always obvious. Many farmers have been applying increasing amounts of inputs to maintain yield levels, so it is not always easy to tell whether or not productivity has declined. And with a few significant exceptions, researchers have not paid sufficient attention to monitoring long-term productivity trends, not even in experimental plots.

Evidence has started to accumulate, however, suggesting that farmers may be right and that there is indeed cause for concern. Throughout South Asia, growth in rice and wheat yields has slowed in recent years, particularly in intensively cropped zones where MVs, fertilizer, and irrigation have been used long and extensively. In areas where rice and wheat yields continue to rise, often the higher yields are achieved by increasing the application of costly inputs, which masks declines in the rate of growth of total factor productivity. Declines in the rate of total factor productivity growth appear to have been brought about by degradation of the natural resource base and the attendant negative ecological effects associated with intensive production systems — declining soil fertility, declining quantity and quality of groundwater, buildups of soil toxicities, and increasing populations of pests. These troubling developments are also being observed in experimental plots, where signs of long-term yield stagnation and natural resource degradation are becoming commonplace.

The faltering productivity of many of South Asia's rice-wheat cropping systems points to an alarming conclusion: agricultural researchers are losing ground in the struggle to devise lasting solutions to the increasingly complex problems confronting farmers. Many policy makers do not appear to be particularly alarmed by this development, expressing confidence that researchers will always be able to devise technological solutions every time a new problem appears. Others are less confident, arguing that some of the resource degradation that is now being observed may by irreversible, so that by the time the extent of the problem is fully appreciated, the damage may be irremediable (and even if the damage can be reversed, doing so may turn out to be prohibitively expensive).

Agricultural research will have to become more effective if the countries of South Asia are to achieve sustainable economic growth while ensuring food security for all. What is needed, however, is not simply more of the same research as has been carried out in the past — not even the same research done better. The commodity-based approach, which was so successful in developing the input-based technologies that spearheaded the Green Revolution, is proving inadequate for developing the knowledge-based technologies needed during the post-Green Revolution era. Given the extremely heavy demands being placed on an already overburdened resource base, a "business as usual" approach is unlikely to generate the technological innovations needed to elicit additional production from South Asia's vital rice-wheat cropping systems. In fact, without dramatic changes in the way research is organized and carried out, it may not even be possible to sustain current high levels of productivity.

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