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Improving the Productivity and Sustainability of Rice-Wheat Systems of the Indo-Gangetic Plains: A Synthesis of NARS-IRRI Partnership Research

J.K. Ladha, K.S. Fischer, M. Hossain, P.R. Hobbs, and B. Hardy, Editors

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Contents

Improving the Productivity and Sustainability of Rice-Wheat Systems of the Indo-Gangetic Plains: A Synthesis of NARS-IRRI Partnership Research

Background

Rice-wheat production systems occupy 24 million ha of cultivated land in the Asian subtropics. In South Asia, the systems occupy about 13.5 million ha (10 million in India, 2.2 million in Pakistan, 0.8 million in Bangladesh, and 0.5 million in Nepal), extending across the Indo-Gangetic floodplain into the Himalayan foothills. Rice-wheat systems cover about 32% of the total rice area and 42% of the total wheat area in these four countries and account for one-quarter to one-third of the total rice and wheat production (Huke et al 1994a,b, Woodhead et al 1994a,b). Although most rice-wheat cropping is fully irrigated, substantial areas are rainfed. The favorable irrigated system with assured water supply has induced farmers to adopt modern cultivars of both cereals. This technology contributed to an impressive increase in per capita production in the irrigated areas in the region from 1965 to 1985. Irrigated rice-wheat systems have remained the major source of the marketed surplus of food grain for feeding the growing urban population.

These gains in food grain production have stagnated, however, for both rice and wheat crops in recent years. There is some evidence of declining partial or total factor productivity (PFP or TFP) (Hobbs and Morris, 1996, Ali and Byerlee 2000, Murgai 2000). The PFP or TFP is the measure of grain output divided by the quantity of a single input or all the inputs taken together, respectively. The causes for the stagnation or decline are not well known, and may include changes in biochemical and physical composition of soil organic matter (SOM), a gradual decline in the supply of soil nutrients causing nutrient (macro and micro) imbalances due to inappropriate fertilizer applications, a scarcity of surface water and groundwater as well as poor water quality (salinity), and the buildup of pests, especially weeds such as *Phalaris minor.* All of these indicate a threat to the ecological sustainability of the system (Paroda et al 1994).

Identifying the processes governing the sustainability of rice-wheat systems in both irrigated and rainfed conditions and to distinguish these from site-specific problems that may be causing a stagnation or decline in productivity are crucial for developing sustainable production technologies. To achieve this, and to develop strategies and tools to preserve and improve these systems, the International Rice Research Institute (IRRI) and International Maize and Wheat Improvement Center (CIMMYT) established a joint research project in 1990 in collaboration with the national agricultural research systems (NARS) of Bangladesh, India, Nepal, and Pakistan in South Asia (Pingali et al 1994). After completing the first phase in 1994, the project members established the “Rice-Wheat Consortium for the Indo-Gangetic Plains” under the leadership of the NARS members. This consortium is a major CGIAR Systemwide Ecoregional Initiative to promote research on issues that are fundamental to achieving enhanced productivity and sustainability of rice-wheat cropping systems in South Asia (Gupta et al 2000, see Box on page 2).

Research conducted during 1990-94 determined the trends in area and yield of rice-wheat systems using geographic information systems (GIS) and district-level secondary data. This led to the monitoring and quantification of the systems at the farm level to identify system constraints, and develop, evaluate, and adapt ameliorative technologies (Hobbs et al 1991, Harrington et al 1993a,b, Hossain 1994, Huke et al 1994a,b, Paroda et al 1994, Woodhead et al 1994a,b,c). The Rice-Wheat Consortium identified four core themes:

- tillage and crop establishment
- nutrient management
- water management
- integrated pest management

and a need to strengthen spatial characterization and GIS, crop improvement, and social science to support the themes.

As a consortium member, IRRI was requested to lead in developing the research strategy for nutrients, and to support work on pest management. IRRI also contributed to environmental characterization and socioeconomic analysis and provided improved germplasm, including hybrids, for the systems. This paper provides a brief overview of recent studies in rice-wheat systems with emphasis on nutrient management conducted by IRRI in collaboration with scientists of the Rice-Wheat Consortium.

The Rice-Wheat Consortium for the Indo-Gangetic Plains

The Consortium was established in 1994 as an Ecoregional Initiative of the Consultative Group on International Agricultural Research (CGIAR), involving the national agricultural research systems of South Asia, international agricultural research centers, and advanced research institutions. The Indo-Gangetic Plains encompass parts of Bangladesh, India, Nepal, and Pakistan and are one of the most productive agricultural areas of the world, feeding many more millions of people than their vast resident population. The Consortium strives to form a network between national and international agricultural institutions to address the issue of enhancing the productivity of rice and wheat in a sustainable manner.

The research agenda is supported by many sources, most notably the NARS members of the Consortium as well as the IARCs. The governments of The Netherlands, the International Fund for Agricultural Development (IFAD), the United Kingdom (through the Department for International Development), Asian Development Bank, and the World Bank (CGIAR Finance Committee’s special funds) have provided funds to support their work at the systems level. The initial years of the Consortium were actively supported by the governments of Sweden and Switzerland and IFAD.

The activities of the Consortium are decided on and approved by the steering committee chaired by the head of four NARS on a rotation basis.

The International Maize and Wheat Improvement Center (CIMMYT) acts as the convening center of the Consortium on behalf of the steering committee and the CGIAR. Consortium activities are implemented by a facilitation unit located in the India Office of CIMMYT in New Delhi.

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System characterization

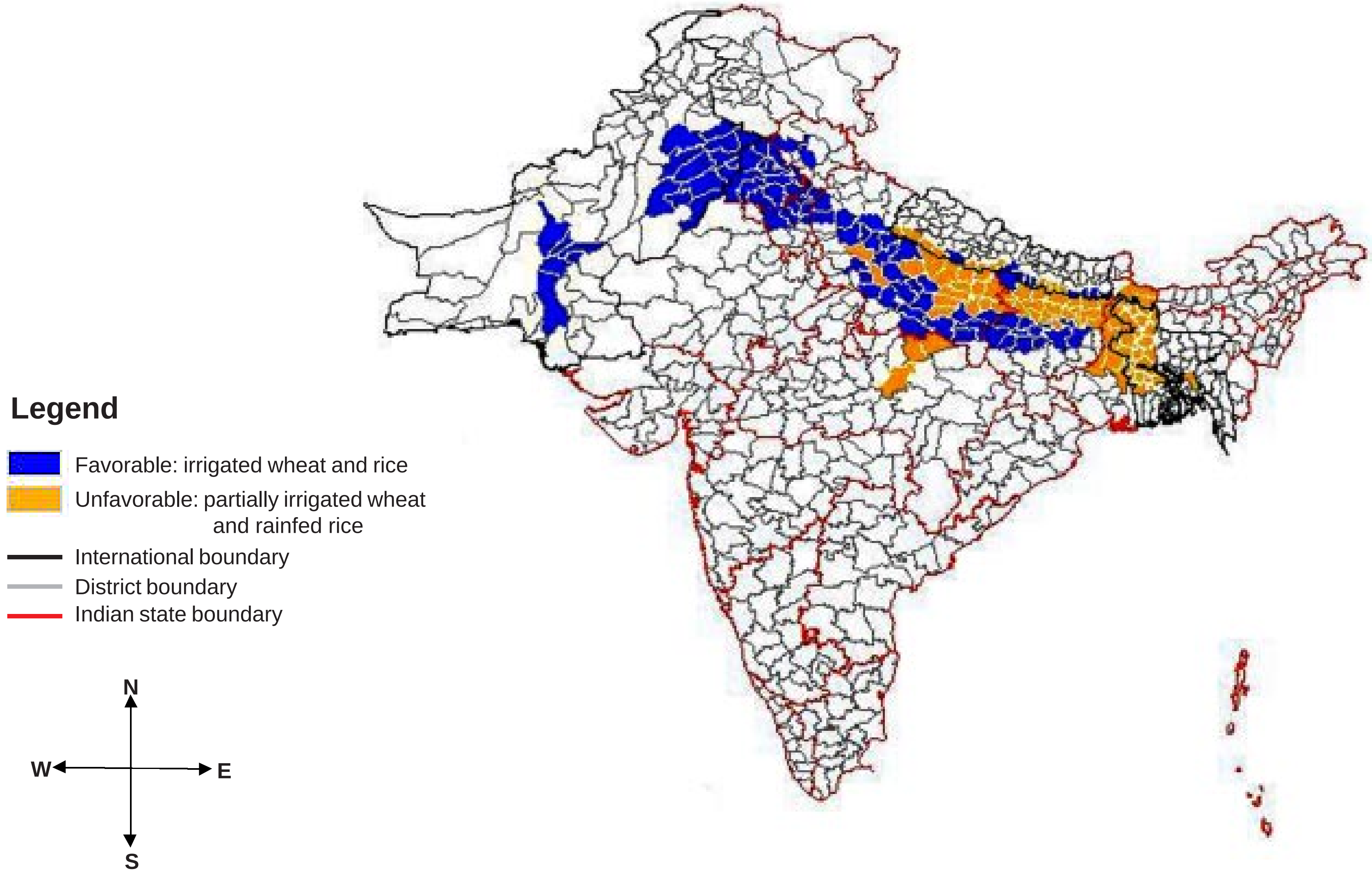
Production environments

The basic characterization of rice-wheat systems was done at the district level. Based on secondary data, two broad categories of rice-wheat systems in the Indo-Gangetic Plains are defined:

1. Favorable rice-wheat environment, constituting districts with predominantly irrigated rice and wheat.
2. Less favorable rice-wheat environment, constituting districts with predominantly rainfed rice and either irrigated or rainfed wheat.

The favorable rice-wheat environment is found mainly in the western part of the rice-wheat belt, where wheat is the dominant crop—in Pakistan, the northwestern Indian states of Punjab and Haryana, and western Uttar Pradesh (Map 1). The less favorable rice-wheat environment occurs in the eastern part of the Indo-Gangetic belt, where rice is the dominant crop—in Bangladesh, West Bengal, the northern parts of Bihar and eastern Uttar Pradesh, and the Terai region of Nepal.

Yields of both rice and wheat are highest in Punjab and Haryana (Table 1). The environmental conditions are favorable for both crops and



Map. 1. An agroecological analysis of rice-wheat area and productivity in the Indo-Gangetic Plains of South Asia.

Table 1. Wheat and rice yields under favorable and less favorable rice-wheat systems in India.

State	Wheat yields (t ha^{-1})			% of wheat area under irrigation[b] 1994-95	Rice yields (t ha^{-1})			% of rice area under irrigation
	1990-93[a]		1996-97[b] (overall)		1990-93[c]		1996-97 (overall)	
	W-R (fav)[d]	W-R (unfav)			W-R (fav)	W-R (unfav)		
Punjab	3.69		4.24	96.7	4.84		5.10	99.1
Haryana	3.57		3.88	98.4	4.29		4.45	99.6
Uttar Pradesh	2.28	2.03	2.66	92.2	3.04	2.45	3.18	60.4
Bihar	1.79	1.71	2.17	87.8	2.29	1.58	2.14	39.8
West Bengal		2.00	2.39	72.5		2.68	3.27	24.6
Madhya Pradesh		1.04	1.76	67.3		1.20	1.75	23.1

Data sources are
[a] Center for Monitoring Indian Economy. India's Agricultural Sector, July 1996.
[b] Department of Economics and Statistics, Ministry of Agriculture, India. 1998. Agricultural statistics at a glance.
[c] Huke and Huke (1997) adjusted to an unhusked rice basis.
[d] Fav = favorable, unfav = unfavorable.

an extensive high-quality irrigation infrastructure exists. Yields average 4.0 and 4.8 t ha^{-1} for wheat and rice, respectively. Wheat yields in the rice-wheat systems are not substantially different from the overall yields for wheat grown in other systems for these states. In contrast, average wheat yields in the irrigated sections of eastern Uttar Pradesh and Bihar are substantially lower (2.0 to 3.0 t ha^{-1}) than those obtained in Punjab, western Uttar Pradesh, and Haryana. This is also reflected in rice yields. This is because of the limited development of the irrigation infrastructure and because of the unreliable supply of irrigation water in these states. Basically, these areas depend on rainfall for the production of both crops, and the irrigation systems were developed to provide supplementary life-saving irrigation during periods of droughts. When reliable irrigation is developed, such as by tubewells and pumps, however, some farmers in West Bengal, India, and Bangladesh prefer to grow rice in both the dry and wet seasons. Their preference for rice over wheat in the dry season (locally called boro rice) is linked to the high temperature and shorter duration of a favorable season for wheat production, and high yield potential of boro rice when water is available.

In the less favorable rice-wheat environment, both rainfed rice yields and wheat yields are substantially lower in Uttar Pradesh and Bihar in India, and Nepal and Bangladesh. In these rainfed rice environments, the wheat crop is only partially irrigated; hence, the growing environment for wheat is also less favorable. Yields are lowest in Madhya Pradesh, where climatic conditions restrict the growth of wheat. Bihar has a larger area under irrigation for both rice and wheat than West Bengal, yet the yields of both wheat and rice are lower than those in West Bengal, indicating the influence of the skewed distribution of land and the insecure crop-sharing tenancy arrangements that affect agricultural productivity in Bihar.

Geographically, the favorable rice-wheat environments in the Indo-Gangetic Plains are located in the western part, where winter environmental conditions are suited for wheat, irrigation infrastructure is good, marketing facilities are available, and both rice and wheat yields are high. The less favorable rice-wheat environments occur in the eastern part and are associated with partially irrigated and rainfed systems, and a shorter growing period for wheat. More detailed agroclimatic analysis would provide an in-depth understanding of the environmental constraints (e.g., drought stress and flood proneness) for geographical targeting of varietal and crop management strategies in both the favorable and less favorable rice-wheat environments.

Spatial and temporal environmental variation

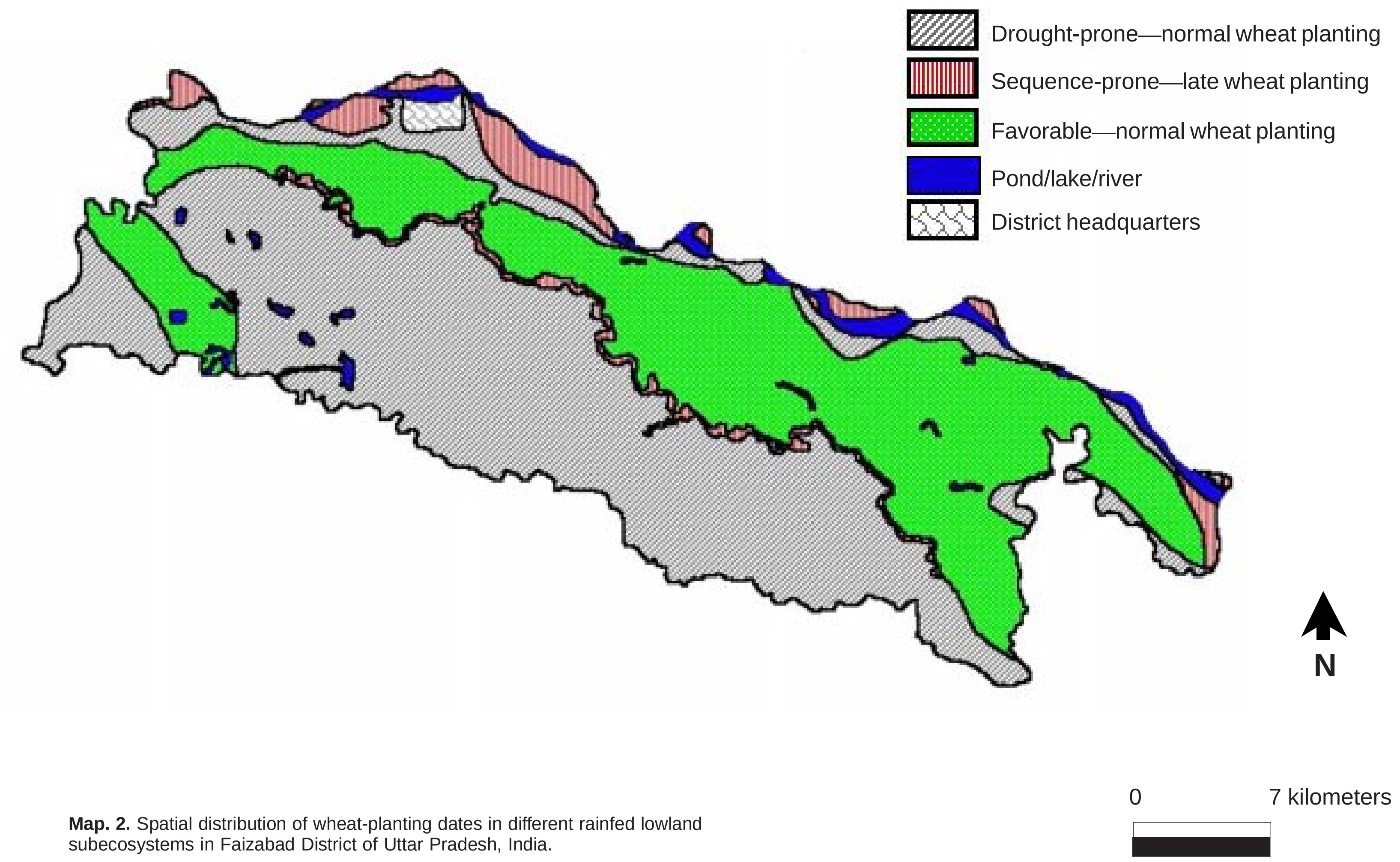
Diagnostic surveys and monitoring (Hobbs et al 1991, 1992, Harrington et al 1993a,b, Fujisaka et al 1994, Ahmed 1995) were conducted to develop baseline reference data on farmers' practices for (1) identifying the factors affecting the adoption of modern varieties and component technologies and (2) quantifying and modeling how farmers' practices vary across agroecological zones and regions, and how these help reduce the risk of crop loss. These analyses were the basis for defining core thematic constraints of the system.

The outputs from the analysis of secondary data using GIS have been published in the *Rice-Wheat Atlas of South Asia* and an individual atlas for India, Pakistan, Bangladesh, and Nepal (Huke et al 1994a,b, Woodhead et al 1994a,b, Singh 1996, Singh and Singh 1996, Huke and Huke 1997). At key sites in eastern India, GIS and remotely sensed data have been used to model and understand how stresses such as drought and flooding vary over space and across years. Based on these experiences, methods for large-scale environmental characterization and technology extrapolation domains are being developed. For example, the rice area (181,000 ha) in Faizabad, a district of eastern Uttar Pradesh classified under the rainfed lowland rice ecosystem, was further delineated into subecosystems; namely, shallow favorable, shallow drought-prone, and shallow submergence-prone (Map 2). The shallow drought-prone rainfed lowlands occupied the largest (51.2%) geographical area of the district, followed by shallow favorable rainfed (39.6%) and shallow submergence-prone rainfed lowlands (6.3%). In addition, the date-wise wheat vegetation maps were prepared from large-scale farmer surveys together with the remote-sensing approach and the entire rice-wheat area was classified into early, normal, and late wheat-planting systems. The submergence-prone area was classified as the late to very late wheat-planted system (wheat sowing in January) or rice-fallow system because of the very long duration (180–210 d) rice varieties used and excessive soil moisture even after the harvest of rice. The entire shallow favorable area was classified as the normal to slightly late wheat-planted system (wheat sowing 15 November to 8 December) because of the use of 120–140 d duration rice varieties, and the drought-prone area was classified as normal to early wheat-planted system (wheat sowing 8–22 November) as farmers in these areas use short-duration (90–110 d) rice varieties and no excess moisture impedes land preparation for wheat sowing.

Such an analysis provides insights into developing suitable technologies, such as rice varieties to be developed according to differential growth duration and crop establishment techniques according to the field moisture regimes in different ecosystems. This also provides a method for delineating the application domain of promising technologies. Three dominant subsystems for the less favorable areas emerge: (1) shallow and favorable for rice and normal planting dates for wheat, (2) shallow and drought-prone for rice and normal planting dates for wheat, and (3) deep and submergence-prone for rice and late planting (or no planting) for wheat.

Characterization of pest profile and yield losses

Relationships among rice-cropping practices, biotic constraints, and rice yields were studied in Uttar Pradesh, India (Savary et al 1997a,b). The investigation was conducted at the center of a geographic area representative of the rice-wheat system of South Asia, and covered a large diversity of production situations undergoing intensification. A survey procedure was used to collect data for three consecutive years (1993-95) in 251 individual farmers' fields. Two analytical approaches were used; the emphasis shifted from yield-determining variables, which are mostly qualitative in nature, to quantitative and predominantly yield-reducing variables. The first approach aimed to characterize relationships among variables using cluster and correspondence analyses, whereas the second approach aimed at generating yield loss estimates using combinations of principal components and step-wise multiple regressions. Different cropping practices were distinguished, reflecting a wide variation in production situations, especially in terms of use of fertilizers and manure and degree of water control. Six types of disease profiles, four insect injury profiles, and four weed infestation patterns were identified.



Map. 2. Spatial distribution of wheat-planting dates in different rainfed lowland subecosystems in Faizabad District of Uttar Pradesh, India.

Correspondence analysis, based on patterns of cropping practices and injury profiles, yielded a path of increasing attainable yield associated with varying levels of intensification and combinations of injuries. The use of principal component analysis with multiple regression generated estimates of yield reduction caused by rice diseases, insects, and weeds (Table 2). The analysis highlighted the effects of changes in patterns of cropping practices on injuries caused by weeds (above and below the rice canopy), brown spot, sheath blight, and deadhearts, as well as the specific importance of these biotic constraints.

The largest individual yield reduction was attributable to a combination of weeds above and below the canopy (a mean yield loss of 0.74 t ha^{-1} and 13% of attainable yield). Deadhearts, brown spot, and sheath blight were responsible for yield losses of 9.2%, 6.6%, and 6.4%, respectively. When all injuries were considered simultaneously, and set to their average values, a yield reduction of 1.4 t ha^{-1} was computed, corresponding to 28.5% of attainable yield. The study indicates that integrated pest management (IPM) recommendation domains and research needs for new IPM strategies can be based on production situations.

Table 2. Yield loss estimates for selected injuries in a rice pest and yield loss study in rice-wheat systems, Uttar Pradesh, India, 1997.

Injury	Mean yield losses		Maximum yield losses	
	Absolute (t ha^{-1})	Relative (%)	Absolute (t ha^{-1})	Relative (%)
Weed infestation above the rice crop canopy	0.30 ± 0.06	6.2 ± 1.2	2.77	55.2
Weed infestation below the rice crop canopy	0.34 ± 0.07	6.8 ± 1.4	2.64	52.6
Deadhearts	0.46 ± 0.07	9.2 ± 1.4	2.63	52.4
Brown spot	0.33 ± 0.03	6.6 ± 0.6	2.43	48.4
Sheath blight	0.32 ± 0.06	6.4 ± 1.2	3.49	69.5
Sheath rot	0.02 ± 0.02	0.4 ± 0.4	0.12	2.4
Neck blast	0.06 ± 0.02	1.2 ± 0.4	1.37	27.3
All injuries combined	1.43 ± 0.27	28.5 ± 5.4	–	–

Source: Savary et al (1997).

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Social and policy issues

Production and price trends

We analyzed the historical data at the country (Bangladesh, Pakistan, and Nepal) and state level (for India) to study the trends in the development of rice-wheat systems, policy issues, and their implications for technology development research (Hossain 1994, 1996, Bhattarai and Pandey 1997).

In eastern India and Bangladesh, where rice is the predominant crop and wheat has unfavorable production environments (shorter duration of winter, heavy soils, and scanty rains during the winter season), rice-wheat systems expanded during the 1970s in response to the food-grain shortage and the availability of higher-yielding wheat varieties. By 1980, the expansion of wheat plateaued at 5% of the area in Bangladesh and West Bengal. In northwestern India and Pakistan, where wheat has a favorable growing environment and rice can be grown only with full irrigation, the system expanded after the early 1970s in response to market opportunities and the availability of high-yielding rice cultivars. Rice gradually emerged as a commercial crop while wheat remained the principal staple food. An analysis of the yield trend shows that, since the mid-1980s, wheat yield has stagnated at around 2.0–2.5 t ha^{-1} in Bangladesh and West Bengal, whereas rice yield continues to increase. In northwestern India, however, rice yield has stagnated and wheat yield increased (Fig. 1). But it is important to mention that, in northwestern India and Pakistan, rice yield is already the highest in the region. In other regions, the yields

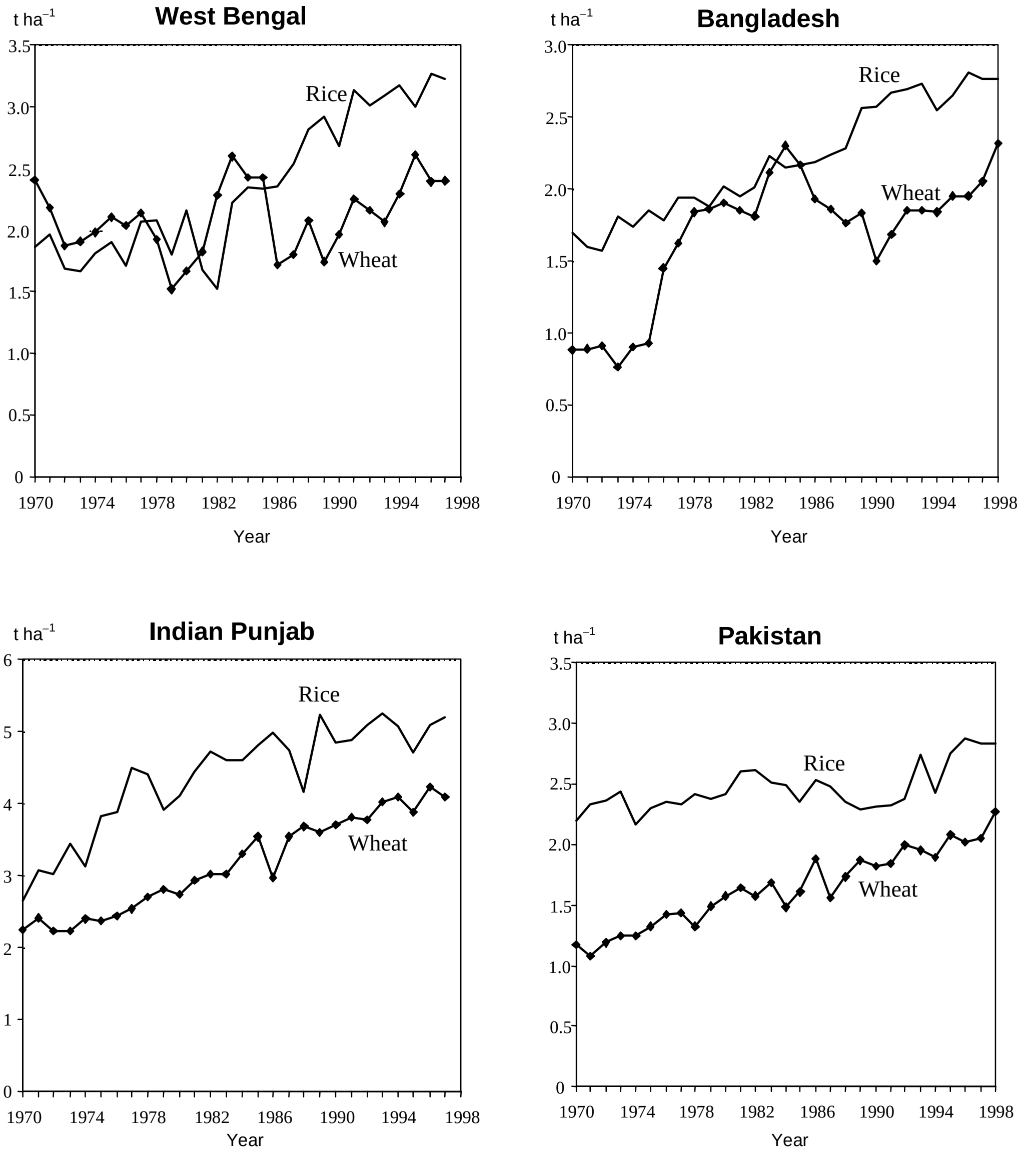

Fig. 1. Trends in rice and wheat yields, selected regions, 1970-98. Sources: FAO Database, 1999 for country data; India Directorate of Economics and Statistics.

of both rice and wheat are steadily increasing (Table 3).

Bangladesh receives a large quantity of wheat (1.0–1.5 million t yr^{-1}) as food aid from wheat-surplus donor countries such as the United States, Australia, and Canada. This should have depressed the prices of wheat in the local market and provided disincentives to the growth of wheat production. An analysis of the long-term trend in prices, however, shows a faster decline in the real price (adjusted for inflation) of rice compared with that of wheat. The price of both rice and wheat generally remained above the world market price. The data indicate that the price trend was not a dominant factor behind the slow growth of productivity of wheat in the unfavorable system.

Information generated on costs and returns shows that boro rice has higher financial and economic returns than wheat. Where the production environment is favorable for both crops (availability of assured irrigation), wheat cannot

Table 3. Growth rates of rice and wheat yields for rice-wheat regions in South Asia (Kam and Hossain, work in progress).

Region	Rice			Wheat		
	Average yield (t ha^{-1})	Rate of growth[a] (% yr^{-1})		Average yield (t ha^{-1})	Rate of growth[a] (% yr^{-1})	
	1996-98[b]	1970-85	1985-98[c]	1996-98	1970-85	1985-98[c]
Bangladesh	2.79	2.03	1.99	2.11	7.71	0.75
Nepal	2.42	–0.16	1.49	1.60	1.76	2.16
India						
West Bengal	3.17	1.20	2.66	2.47	0.58	2.09
Bihar	2.11	0.69	2.28	2.07	1.42	2.89
Uttar Pradesh	3.07	3.64	3.35	2.57	3.75	2.53
Punjab	5.00	3.61	0.66	4.07	2.88	1.97
Haryana	4.01	3.42	0.70	3.75	3.05	2.33
Pakistan	2.84	0.71	1.51	2.11	2.58	2.06

[a] Estimated by fitting semilogarithmic trend lines.
[b] Refers to average yield for 1995-97 in selected states of India.
[c] Refers to rate of growth for 1985-97 in selected states of India.

compete with dry-season rice. Wheat, however, has a comparative advantage in areas with a longer duration of winter and light soils. The year-to-year variation in area under wheat was related to the price of wheat relative to that of the competing crop. But the long-run variation in area under both wheat and rice was price-inelastic. For Nepal, the price response for wheat was higher in areas with assured irrigation and access to developed infrastructure.

These findings suggest that agro-climatic and technical factors are more important contributions to increasing the productivity of rice-wheat systems than economic factors.

Quantifying rice-wheat systems' contributions to livelihood: a case study in the unfavorable rice-wheat system

We studied farming systems and gender roles by generating household-level data for two villages in eastern Uttar Pradesh, the heartland of rice-wheat systems (Paris et al 1996). The survey covered 288 households. Rice-wheat and rice-wheat mixed with mustard were the predominant cropping patterns, accounting for 50–60% of the total cropped land. Rice and wheat are grown as staple foods, whereas their straws are mainly used as feed for livestock. Despite the importance of rice and wheat in cropped area, the system's contribution to household incomes was very low: 11% in the village nearest to the market town where households have greater access to other income-generating activities; 22% in the remote village where agriculture is the predominant source of livelihood. Non-farm income (52%) and livestock (27%) are the major sources of household income. The rest of the income comes from other crops and the sale of farm by-products.

Of the total rice-wheat farming households (243), 72% have marginal (<0.25 ha), 22% have small (0.26–0.5 ha), and 6% have medium-sized (0.51–1.0 ha) landholdings. A higher proportion of these smallholder households are engaged in subsistence livestock raising (65–87%) and nonfarm (74–89%) earning opportunities.

Within these small cultivating households, female family members provide most of the labor for crop and livestock activities and are highly dependent on by-products of rice and wheat for livestock feed. As men seek employment and income-earning opportunities in the nonfarm sector, often through temporary migration, women in a large proportion of households manage the farm. The de facto female-headed households were 30% higher in the village nearest to the market town. Gender analysis showed that the labor requirements for rice and wheat production are met mostly by women from the lower social status. Figure 2 shows the share of time dedicated by men and women to

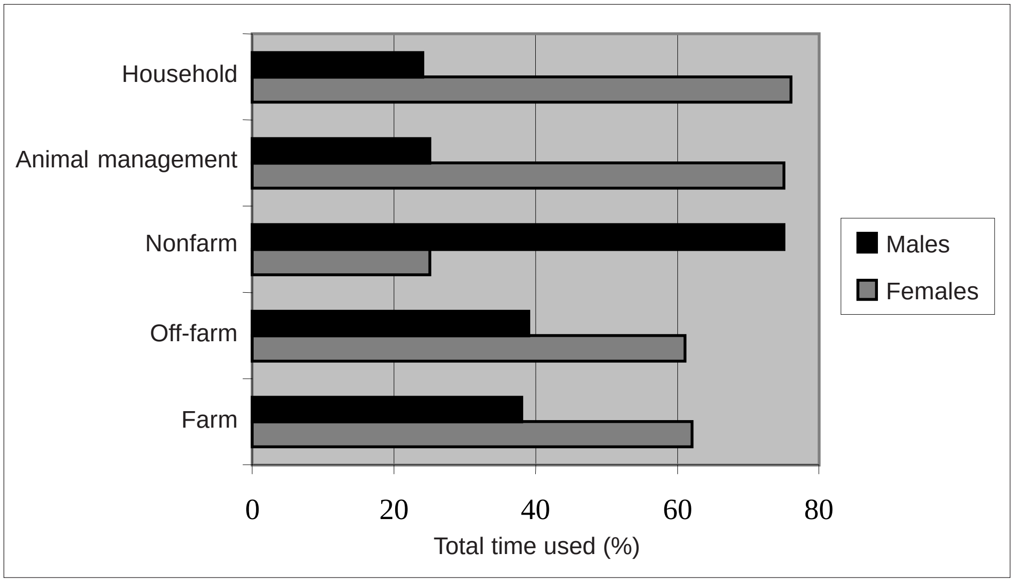

Fig. 2. Time allocation of principal male and female family members, Mungeshpur village, Faizabad (Paris et al 1996).

household, animal management, farm, off-farm, and nonfarm activities. Although women contribute the major portion of labor for household activities, for crop production, animal raising, and off-farm work, three-fourths of the labor in nonfarm activities is contributed by men. Postharvest activities in rice and wheat such as dehusking, seed selection, and seed storage and food preparation carried out within the homestead are done exclusively by female family members. As rice and straw are major sources of animal fodder, women consider quantity and quality of straw important criteria when selecting modern varieties.

These findings have important implications for rice-wheat systems research in terms of developing varieties with high quality and quantity of biomass for animal fodder, designing cropping patterns wherein the peak of rice-wheat crop management does not conflict with the timing of nonfarm employment, introducing improved varieties suitable to the system, and increasing the participation of farmers (including women) in improving seed selection, storage practices, and cultural management of rice-wheat cropping systems.

Systems sustainability

Productivity trends in intensive cropping systems

Trends of rice and wheat yields. IRRI's Medium-Term Plan outlines two core projects under the Irrigated Rice Research Program to do research on the sustainability of intensive rice-cropping systems, focusing on rice-rice and rice-wheat systems. This research began in response to declining yields in some long-term experiments (LTEs) and concerns that the productivity of intensive rice and rice-wheat systems may be stagnating or declining (Flinn et al 1982, Flinn and De Datta 1984, Cassman and Pingali 1995, Woodhead et al 1994c, Regmi 1994). More recent reviews of productivity trends can be found in Hobbs and Morris (1996), Ali and Byerlee (2000), Murgai (2000), Dawe and Dobermann (1999), Dawe et al (2000), and Dobermann et al (2000).

Yield decline refers to a decrease in grain yield over a period of at least several years (Dawe and Dobermann 1999). In the context of experiments on research stations, the term usually refers to a decline in the measured experimental yields of the highest-yielding cultivars under constant input levels and management practices. Regression analysis is typically used to assess the statistical significance of measured trends relative to year-to-year fluctuations in yields. A recent analysis of yield trends in 30 long-term rice experiments with rice-rice or rice-wheat systems conducted in seven different Asian countries (China, India, Indonesia, Bangladesh, Vietnam, the Philippines, and Malaysia), covering a wide variety of soil types, suggests that yield declines are not very common, particularly at yields of 4 to 7 t ha^{-1} (Dawe et al 2000). Of the seven long-term rice-wheat experiments we examined, none had a significant yield decline in the wheat crop, but rice yields in the Pantnagar-LTFE (long-term fertility experiment, started in 1984) in India declined at a rate of 2.3% per year (Table 4 and Fig. 3). The rice yield decline at the Ludhiana-LTE (2.7% per year) was not statistically significant ($P = 0.126$). In all six other rice-wheat LTEs studied, rice yield in the best fertilizer treatments remained unchanged over periods of 10 to 25 years. Several rice-wheat sites in India and Nepal, however, reported a yield decline, mainly for the rice crop (Regmi 1994, Nambiar 1995, Yadav 1998, Duxbury et al 2000). Duxbury et al (2000) showed that 8 out of 11 long-term rice-wheat experiments that had run for more than 8 years showed a downward trend in rice yields over time. This contrasted with only 3 of 11 showing a downward trend in wheat. A few LTEs that examined the effects of organic manure on yield showed either no or less yield decline in rice-wheat systems than in treatments without organic manure.

Long-term experiment analysis depends on fitting nonbiological functions to data over time. Some of the variation in yield, however, may be related to seasonal changes and long-term changes in variables other than those associated with sustainability. Process-based models have

Table 4. Yield trends in rice-nonrice (wheat) long-term experiments. Values shown include the duration for which the linear regression was computed, the magnitude, t-statistic, and *P*-value for the slope (time trend), and the initial grain yield (average of first 3 years). The experiments are listed in ascending order according to the t-statistic (Dawe et al 2000).

Long-term experiment[a]	Duration	Rate of annual yield change			Initial yield (t ha^{-1})
		Magnitude	t-stat	*P*-value	
Rice					
Pantnagar-LTFE	1984-98	–0.0233	–5.098	0.000	7.17
Ludhiana-LTE	1991-99	–0.0267	–1.739	0.126	6.15
Barrackpore-AICRP	1973-97	–0.0058	–0.910	0.373	4.75
Sichuan-LTE (late rice)	1984-93	–0.0129	–0.905	0.392	6.07
Karnal-LTE	1974-85	–0.0064	–0.606	0.558	6.83
Zhejiang-LTE (late rice)	1977-93	–0.0015	–0.200	0.844	6.27
Pantnagar-LTE	1978-98	0.0076	0.717	0.483	4.10
Nangong-LTFE	1983-96	0.0079	0.784	0.448	6.02
Sichuan-LTE (early rice)	1984-93	0.0147	0.959	0.366	5.21
Zhejiang-LTE (early rice)	1977-93	0.0273	1.196	0.250	2.56
Average rice		–0.0019	–0.580	0.384	5.51
Wheat					
Pantnagar-LTFE	1984-98	–0.0195	–2.038	0.066	3.68
Nangong-LTFE	1984-96	–0.0367	–1.558	0.148	2.75
Sichuan-LTE	1984-93	–0.0166	–1.255	0.245	3.89
Barrackpore-AICRP	1972-96	–0.0014	–0.302	0.765	3.22
Ludhiana-LTE	1991-99	0.0164	1.696	0.134	4.53
Karnal-LTE	1975-86	0.0366	1.979	0.076	4.10
Pantnagar-LTE	1978-98	0.0240	3.409	0.003	2.97
Average wheat		0.0004	0.276	0.205	3.59
Other crops					
Barrackpore-AICRP (jute)	1972-97	–0.0093	–2.882	0.008	2.68
Zhejiang-LTE (barley)	1977-93	0.0150	2.607	0.018	4.42

[a] LTE = long-term experiment, LTFE = long-term fertility experiment, AICRP = All India Coordinated Research Program.

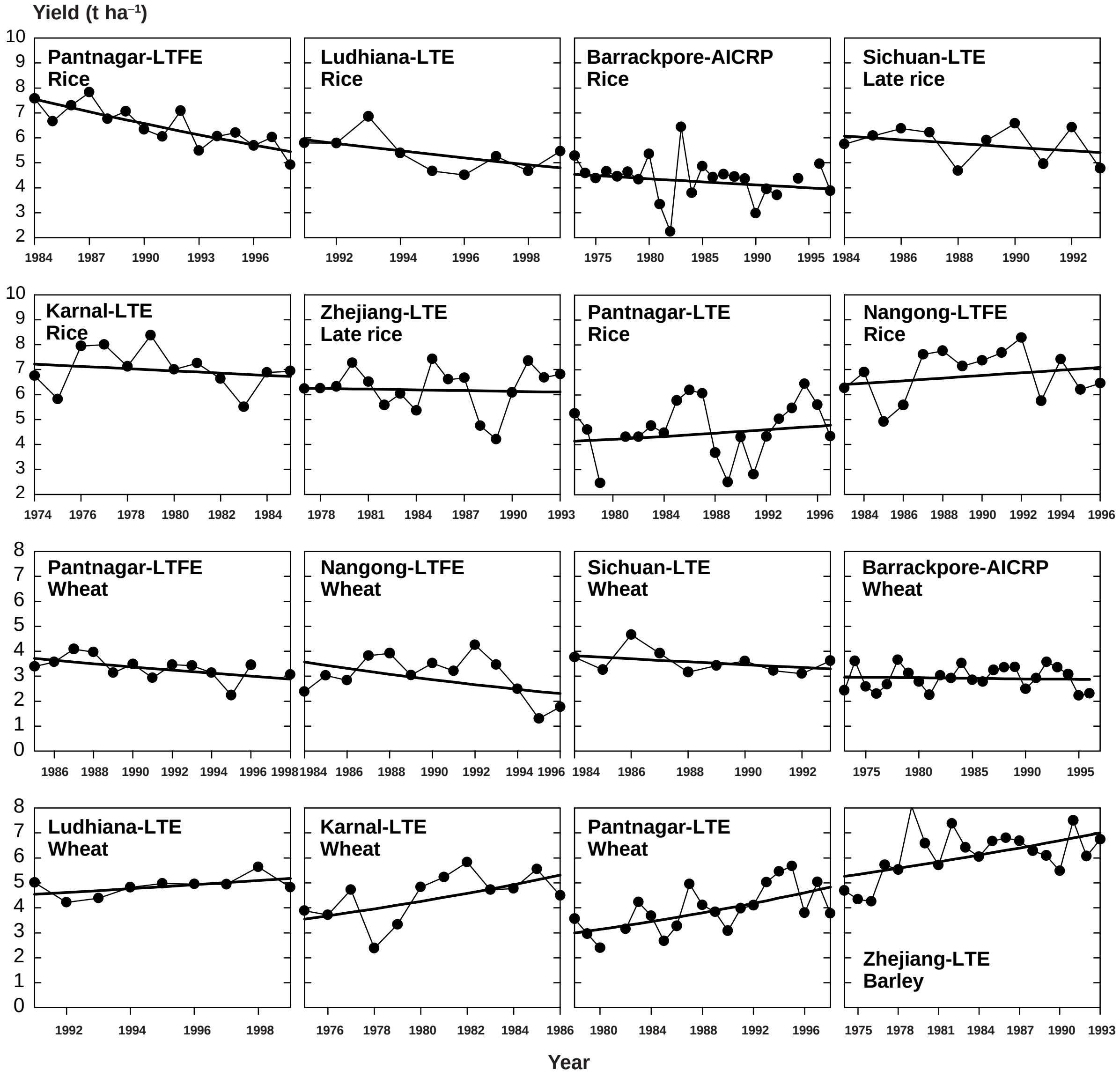

Fig. 3. Trends of grain yield of rice and wheat in long-term experiments (LTEs) with rice-wheat systems. Measured mean yields of the treatment with the highest NPK rate in the highest-yielding climatic season at each site (symbols) and the trend line fitted by linear regression (Table 5) are shown. The LTEs were plotted in the same order as shown in Table 5, but excluding the early rice crops at Sichuan- and Zhejiang-LTEs (Dawe et al 2000).

been used in rice to examine the trend in yield when all nontreatment variables are held constant. Likewise, models have been tried for rice-wheat systems by combining various approaches (Timsina et al 1994, 1995, 1996, 1998). IBSNAT/IFDC-based CERES-rice and CERES-wheat models, and Wageningen-based ORYZA1 and WHEAT_W models using data sets from Pantnagar, India, and Nashipur, Bangladesh, predicted rice and wheat yields at medium to high levels (see Figs. 4 and 5 for simulations at the Pantnagar site). These models confirmed a yield decline over time. The models were not able, however, to examine the separate effects of declining soil organic matter and N supply. The models are nevertheless a useful tool in systems analysis.

A recent analysis of yield trends of several long-term experiments, mostly rice-rice, suggests that yield declines do not appear to be as widespread as once believed, particularly at current yields of 4 to 7 t ha^{-1}. Although in rice-wheat systems relatively fewer long-term experiments examined seemed to indicate a yield decline for rice, there is a need to analyze more long-term experiments to clarify yield declines in rice-wheat systems.

The results of model validation and extrapolation suggest a continual need for further refinement of existing models to realistically simulate yields of rice-wheat systems and soil parameters and to confidently explain productivity trends across sites and seasons.

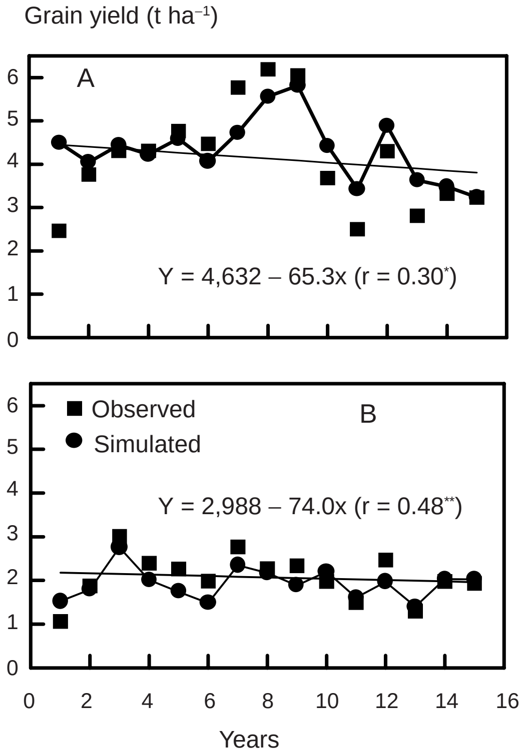

Fig. 4. Long-term simulated and observed grain yields of rice at (A) 120 kg N ha^{-1} and (B) zero N for a long-term experiment at Pantnagar, India (year 1 = 1979, year 15 = 1993, Timsina et al 1996).

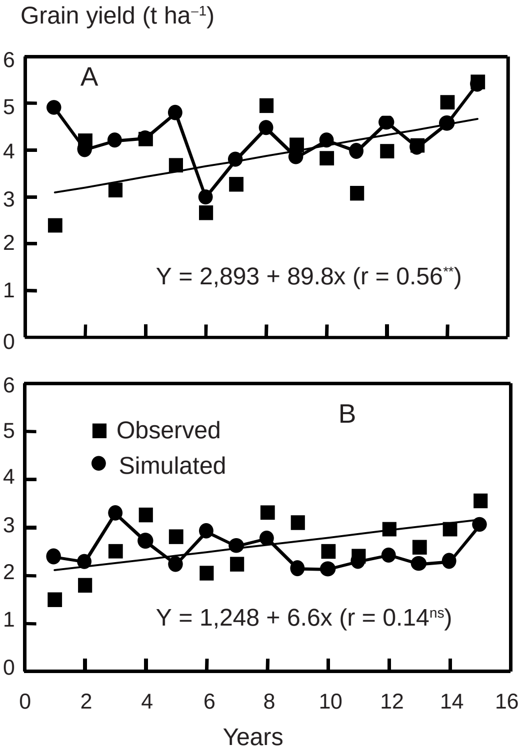

Fig. 5. Long-term simulated and observed grain yields of wheat at (A) 120 kg N ha^{-1} and (B) zero N for a long-term experiment at Pantnagar, India (year 1 = 1979, year 15 = 1993, Timsina et al 1996).

Possible causes of yield decline. An analysis of input-output balances of N, P, and K at some of these LTE sites showed that depletion of soil nutrients caused by years of intensive cropping is a common feature that appears to contribute to the observed yield decline (Regmi 1996, Yadvinder-Singh et al 2000). In addition to mining of nutrients, there is some evidence of changes in the availability of nutrients to the plant. In most rice-wheat experiments, the soil organic matter declines over time. But it is not only the decline per se; there may also be changes in the chemical composition of organic matter (Olk et al 1996, 1998, Bronson and Hobbs 1998) that influence the capacity to supply N to the plant. One hypothesis currently being studied is that of a buildup of phenolic substances as a component of the SOM altering the release of N from the soil. There appears to be evidence of this happening in the almost continuously flooded soils of the rice-rice intensive systems (Olk et al 1996). Preliminary analyses of humic acids extracted from the sites of a long-term rice-wheat trial in Pantnagar, India, revealed that the diversity and concentrations of phenolic compounds were similar to those of humic acids from continuous rice soils, although the phenols of the rice-wheat soil were more oxidized than those of continuous rice (IRRI 1998). In both cases (rice-rice and rice-wheat), the pattern of humic acid buildup is very different from that in upland (aerated) systems. These results imply that SOM formation in well-irrigated rice-wheat systems in South Asia more closely resembles that of continuous rice than that of rice-upland crop rotations in the humid tropics. Low organic-C levels of the soils, however, more closely resemble those of rice-upland crop soils, suggesting that SOM degradation in rice-wheat soils is faster than in soils under intensive rice-rice cultivation (Bronson et al 1998).

There may also be changes in the timeliness of the availability of soil N that influence physiological processes and yield. Thus, in one long-term trial at IRRI, the reduction in yield appears to be associated with a change in physiological N-use efficiency of the rice plant (measured as grain yield increase per unit increase in plant N) and not with the amount of N taken up by the plant (Ladha et al 2000). Such a change could take place if N was not available to the crop at a critical phase of growth.

Recently, in a detailed analysis of a long-term rice-rice-wheat experiment conducted at Bhairahawa (Nepal), we found that wheat yields declined because of a delay in planting (Regmi et al, unpublished). When planting date differences in years are used to adjust yield in the experiment, no wheat at full NPK or FYM treatment has significant yield decline slopes.

These recent investigations suggest that a better analysis and interpretation of results of long-term experiments can provide valuable information for the issues of sustainability and resource management. Long-term experiments should be monitored constantly and the data analyzed using improved statistical and simulation tools.

Long-term experiments are valuable for understanding the relationships between changing soil and crop management practices and productivity. It is important that we constantly monitor these experiments and analyze the data collected using improved statistical and simulation tools.

We are currently assessing the quality changes in soil organic matter in rice-wheat systems in both long-term experiments and farmers' fields of different soil types and management practices, including application of crop residues of varying quality. A large database with a wide range of total and biologically active SOM pools will help in establishing relationships among various SOM quality, soil fertility, and crop productivity parameters, and identifying appropriate soil quality indicators.

Trends of factor productivity. Assessing sustainability in farmers' fields is considerably more difficult than on experiment stations because farmers adjust their inputs substantially from year to year. In this context, different measures of productivity are a more appropriate yardstick than are yield trends. Yield is a form of productivity measurement, the productivity of land, but there are many other measures of productivity (Dawe and Dobberman 1999). One example is the partial factor productivity (PFP) of fertilizer, which is the average productivity, measured by grain output divided by quantities of fertilizer. This is relatively easy to measure, but its interpretation is not clear. Some studies have calculated trends in the partial factor productivity of fertilizer (PFP-F) over time. Invariably, these calculations show sharply declining trends, and they are cited as a cause for concern. Long-term trends in PFP-F are highly misleading as indicators of sustainability, however, because most of the decline in PFP-F is due to movement along a fertilizer response function, as opposed to a downward shift of the response function itself. The former is not a cause for concern, as it is merely a reflection of the fact that farmers took some time to learn about optimal levels of fertilizer usage. For example, survey data for a group of farmers in

Central Luzon in the Philippines show that it took 10 to 15 years after the introduction of modern varieties for average N use in the wet season to increase from 10 to 60 kg ha^{-1}. And the spread of higher levels of fertilizer use from one area to another has also taken time, requiring the transmission of knowledge and the construction of irrigation systems. Thus, as modern varieties spread and farmers learned about fertilizer, fertilizer use increased sharply. Since nitrogen response functions are highly concave, this large increase in fertilizer use has led to a sharp decline in the PFP-F. But this decline in the PFP-F is of no concern and does not imply a lack of sustainability in the system.

The data with which to measure TFP at the farm level are difficult to collect because they require a large amount of detail, including the prices and quantities of all inputs and outputs. Nevertheless, two recent studies by Ali and Byerlee (2000) and Murgai (2000) have estimated trends in TFP in the rice-wheat systems of Pakistan and India, respectively. Ali and Byerlee (2000) calculated TFP growth rates on a cropping systems basis in Pakistan's Punjab from 1966 to 1994. They found positive TFP growth of 1.26% per annum for the entire period for all systems considered together. Growth was positive in the wheat-cotton and wheat-mungbean cropping systems, but was negative in the rice-wheat system, especially in the early years of the Green Revolution (1966-74). Perhaps surprisingly, TFP growth in the rice-wheat system was increasing over time, and was +0.88% per year from 1985 to 1994. Relatively rapid TFP growth in this latter period suggests that there is no imminent crisis of sustainability.

Using district-level data from the Indian Punjab, Murgai (2000) found a similar pattern of relatively slow productivity growth in the early years of the Green Revolution. She argues that this pattern occurs because the technical change induced by the Green Revolution was not Hicks-neutral, that is, it favored increased use of certain inputs relatively more than others. Under such conditions, estimates of TFP growth are biased indicators of technological progress. She found that TFP growth from 1985 to 1993 was greater than 1.5% per annum in eight of nine districts in Punjab and Haryana. The only exception was in Ferozepur, where wheat-cotton is the dominant cropping system. According to Murgai (2000), the evidence in India's Punjab "suggest(s) that fears about unchecked reductions in productivity growth are exaggerated."

It is important to remember that TFP does not directly measure environmental degradation. In fact, Ali and Byerlee (2000) found substantial deterioration of soil and water quality in all cropping systems in Pakistan's Punjab, including those with positive TFP growth. It was most severe in the wheat-rice system, where it reduced TFP growth by 0.44% per annum during the period 1971-94. If TFP growth is positive in the presence of environmental degradation, this indicates that technological progress and improved infrastructure have more than compensated for the environmental degradation. Even if this has happened in the past, however, this is no guarantee that it will continue in the future.

The studies by Ali and Byerlee (2000) and Murgai (2000) relied on secondary data sources to estimate trends in TFP. In collaboration with researchers at G.B. Pant University of Agriculture and Technology in Pantnagar, Uttar Pradesh, India, IRRI researchers have been collecting the primary data needed to measure changes in TFP in the fields of farmers practicing rice-wheat rotations (data collection is also ongoing at seven other rice-rice or rice-maize sites elsewhere in Asia). Furthermore, data on biophysical variables are also being collected. Although not necessary for measuring TFP, these biophysical data are crucial for understanding why TFP is changing, which is obviously important for devising appropriate intervention strategies.

Trends in PFP-F can be highly misleading if not interpreted carefully. Therefore, it is highly preferable to calculate trends in total factor productivity or use production functions to assess sustainability. Unfortunately, the data requirements for measuring TFP are much greater than for PFP-F, and not many long-term farm-level data sets have the necessary data. This work is in the data collection phase of the study, with the first analysis planned in 2002.

Conserving soil N

Intensified lowlands of Asia can be grouped into two dominant patterns with respect to soil conditions that influence N supplies. In a large area, rice-rice is dominant and the soil is under anaerobic conditions for much of the time.

In the other area, the common cropping sequence is a dry-season (DS) upland (irrigated) crop, a fallow (dry-to-wet transition), and wet-season (WS) rice. Thus, a typical sequence in the subtropics is wheat or maize or legumes as dry-season crops followed by rice. The alternate soil wetting (anaerobic) and drying (aerobic) in this system create particular difficulties for N conservation (Kundu and Ladha 1999). Soil N mineralized and nitrified at the onset of rains in the fallow may be lost by leaching and by denitrification when the soil becomes submerged for rice. Thus, N balance has been the focus of many studies in rice (Ladha et al 1996, Tripathi et al 1997, Shrestha and Ladha 1998).

An extreme case of N use was reported in one study when high-value crops are grown in the dry season. Under these conditions, N losses in farmers' fields ranged from 240 kg ha^{-1} yr^{-1} with a DS tobacco crop to 575 kg ha^{-1} yr^{-1} with a sweetpepper crop (Tripathi et al 1997). Much of this N leached into groundwater in the sweetpepper areas. Some 50% of the wells sampled had NO_3-N concentrations exceeding WHO limits (Shrestha and Ladha 1998). The following transplanted rice crop was unable to capture the high levels of N that were in the system at the end of the dry season.

In another study of highly intensified systems involving rice-wheat-rice, rice-legume-rice, and rice-fallow-rice systems, only direct-seeded rice benefited from the residual N; when rice was transplanted, most of the accumulated N was lost upon flooding.

Cultural practices of stubble management, seeding, and water all influence the interaction of N, particularly conservation of N during the transient period. The extent of N loss in rice-wheat systems and opportunities to modify cultural practices are an area for further research. It is postulated that the pattern of N and C dynamics and balances in rice-wheat systems are expected to be similar to those of tropical rice-upland crops and that the temperature during the dry season will affect the magnitudes of these processes. We will examine the use of diverse crops, particularly legumes, during the dry-to-wet transition in rice-wheat to conserve and recycle soil N.

Synchronizing N supply with crop demand

The optimum use of N comes from matching supply with crop demand. In many field situations, up to 50% of applied N is lost due in part to the lack of synchrony of plant N demand and N supply. This lack of synchrony reduces the physiological use of the N available to the crop. In the past, the timing of fertilizer to best match demand with supply has been based on regional recommendations. However, a growing body of evidence indicates large farm-to-farm and plot-to-plot variation in N supply and capacity of the soil to meet crop demand. In developed-world agriculture, the concept of precision farming is rapidly growing. An issue in Asia is the extent to which this principle, that is, crop demand-driven site-specific application, can add to farmers' profits. We have begun by initially developing a simple "researcher" system for identifying crop demand to examine the effectiveness of the concept and then to modify and adapt the concept to develop a profitable technology appropriate for small Asian farmers. Two potential solutions have been tried to regulate the timing of N application in rice and wheat: (1) use of a chlorophyll meter or leaf color chart based on the actual needs of the plants, and (2) improved N fertilizer formulations and deep placement of fertilizers.

Chlorophyll meter as a diagnostic tool to measure leaf N status. We use the chlorophyll meter (or SPAD meter), a reliable and nondestructive tool, to determine the right time of N topdressing for rice and wheat crops (Peng et al 1996, Balasubramanian et al 1999). The concept is based on results that show a close link between leaf chlorophyll content and leaf N content. Thus, the chlorophyll meter can be used to quickly and reliably assess the leaf N status of crops at different growth stages. Based on a large number of experiments both at NARS research stations and in farmers' fields carried out through the Crop and Resource Management Network

(CREMNET), 20–25% of the N fertilizer input was saved without reducing rice grain yield.

Unlike rice, where N can be topdressed two to four times during the growth period, N application in wheat is linked to irrigation. We evaluated the use of a SPAD meter in wheat to determine whether a topdressing was needed and, if so, how much (Bijay-Singh et al 1997). Experiments conducted at Ludhiana, India, indicated that wheat yield is likely to respond with a topdressing of 30 kg N ha^{-1} when the SPAD reading at maximum tillering is less than 44 (Fig. 6).

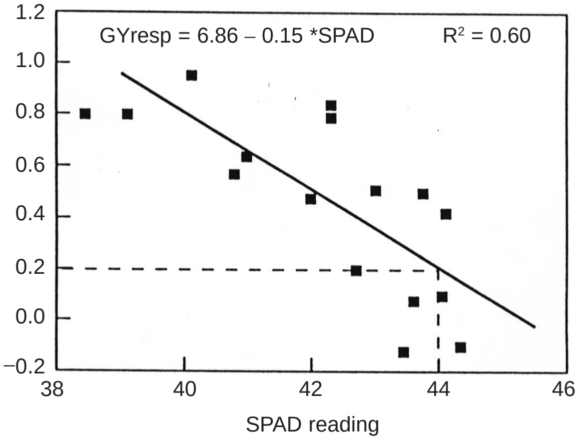

Fig. 6. Relationship between wheat grain yield response to N at maximum tillering (MT-N) and SPAD readings (Bijay-Singh et al 1997).

Leaf color chart—a simple, inexpensive N management decision tool for farmers in rice-wheat systems. The cost of the SPAD meter restricts its widespread use by farmers. Because the SPAD meter measures leaf color as a proxy for leaf N, a simplification of this is to use the green color as an indicator. Hence, we have adapted and simplified the concept. In collaboration with PhilRice, a leaf color chart (LCC) from a Japanese prototype that can help farmers measure the leaf color intensity and relates to leaf N status has been developed (IRRI 1999). The LCC is an ideal tool to optimize N use, irrespective of the source of N applied—organic, bio-, or chemical fertilizers. It is thus an ecofriendly tool in the hands of small farmers. It costs about US$1 per piece. It is being introduced to farmers through field researchers, extension staff (government and nongovernment organizations), and private-sector agencies. During 1997-99, more than 35,000 LCC were distributed to farmers in several rice-growing countries. Several NARS scientists and farmers were trained on the use of the LCC.

Urea tablet or briquette deep placement. Deep placement of urea tablets, urea briquettes, or urea supergranules below the soil surface (8–10-cm depth) can improve fertilizer N uptake by rice and reduce N losses, particularly from ammonia volatilization. This technique is especially effective for rice environments with variable moisture conditions. A single application of N by deep placement is made at 7–14 d after transplanting or 10–20 d after direct seeding of rice. With deep placement, a steady and adequate supply of N is made available to the crop for a relatively longer period of time. This practice can increase grain yield and N-use efficiency, and reduce the fertilizer requirements of a crop by 30% to 50% in clay, clay-loam, and loamy soils with low percolation rates (Mohanty et al 1999).

IRRI collaborates with the USAID-funded and IFDC-executed Agrobased Industries and Technology Development Project (ATDP) in Bangladesh to promote this technology. The ATDP and Mark Industries (private sector) have perfected a urea briquette machine. It costs US$2,200 per unit and produces 250 kg of urea briquettes per hour. By June 1999, more than 100 urea briquette machines had been sold to private entrepreneurs who produce urea briquettes for rice farmers in their respective locations. In Bangladesh, the cost of urea briquettes is about 10% higher than that of prilled urea. During 1999, more than 100,000 ha of boro rice were fertilized with urea briquettes.

The farmers' major problem is the difficulty of manual deep placement of urea briquettes, especially in randomly transplanted rice. Development of a suitable, cost-effective deep-placement machine is still a challenge to engineers. In the meantime, a hand applicator, developed and tested in Indonesia, has been produced for evaluation in India and Myanmar. It costs about $8 per unit.

Controlled-release fertilizers. Controlled-release fertilizers are available that have an ultrathin membrane polymer coating that encapsulates a urea granule. The release of nutrients through this membrane occurs in a predictable manner. Following absorption of soil moisture by the polymer coating, the release of urea occurs as the encapsulated urea dissolves and diffuses slowly and continuously through the membrane. Controlled-release fertilizers from two sources were evaluated in Bangladesh, India, Indonesia, and the Philippines during 1997-99. A single basal application of controlled-release fertilizer before crop establishment steadily released N for crop uptake throughout the growth period, increased grain yields, and reduced the N fertilizer requirement by 30% to 50% compared with split application of prilled urea as per local recommendations (Balasubramanian and Morales 1998). The controlled-release fertilizer also provides the opportunity for placement of fertilizer with seed (Shoji and Kanno 1994). Controlled-release fertilizers are relatively more effective in reducing nitrate leaching and nitrous oxide emissions. Since the rate of urea release is controlled, large changes in pH and phytotoxicity due to high ionic strength do not occur. Thus, a combined operation for seed and fertilizer application is feasible. Seed-fertilizer placement is likely to reduce the labor cost. However, the relative price of controlled-release fertilizer in relation to prilled urea will determine its commercialization potential for rice-wheat systems. A price of controlled-release fertilizer at about 25% higher than that of prilled urea will be very attractive to farmers.

Managing phosphorus

Phosphorus is an extremely immobile nutrient in the soil. It is adsorbed very strongly to soil particle surfaces and quickly forms stable compounds by reacting with common soil constitutes such as iron, aluminum, and calcium. The P assumes particular importance in rice-wheat cropping systems because of wetting and drying, resulting in soils being exposed to alternate anaerobic and aerobic conditions. After soil flooding, the reduction in ferric iron phosphate compounds and increase in the solubility of Ca-P compounds result in greater P availability to rice. But subsequent draining of the rice fields increases P absorption and P immobilization during the wheat phase (Ponnamperuma 1972). Because of complex P dynamics in rice-wheat systems, farmers apply an insufficient to excessive amount of P to wheat and rice, resulting in an unsustainble system.

Using a long-term experiment comprising varying levels of P fertilizer for wheat and rice on a loamy sandy soil at PAU, Ludhiana, researchers developed a P management strategy that is agronomically sustainable and economically viable (Yadvinder-Singh et al 2000).

A sustainable P management strategy must ensure (1) high and stable overall food production, (2) high annual profit, and (3) sufficient P supply for potential yield increases. A normal practice of applying 26 kg P ha^{-1} to wheat only in rice-wheat systems resulted in lower P accumulation and profit, a negative P balance, a decline in available soil P, and lower agronomic efficiency of P (AE_p) and recovery efficiency of P (RE_p) of wheat, although, on average, rice yields were not significantly smaller than in treatments when some P was also applied to rice. The agronomic indicators in our experiment suggested that (1) the total P input should be in the range of 40 to 50 kg P ha^{-1} yr^{-1}, (2) at

A large volume of published information is available to demonstrate that the fertilizer N-use efficiency of a crop can be increased 30% to 50% by using the chlorophyll meter/leaf color chart, urea deep placement, and controlled-release fertilizers. In rice, these practices have been successfully evaluated on-farm and are in the process of economic and impact analysis. In rice, the future need is to continue to expand a vigorous on-farm technology evaluation and adoption program, whereas in wheat more research is needed to determine the usefulness of different techniques. In addition, development of a suitable, cost-effective deep-placement machine is urgently needed.

least 26 kg P ha^{-1} must be applied to wheat to achieve wheat yields of >5 t ha^{-1}, and (3) not more than 15 to 25 kg P ha^{-1} should be applied to rice. Economically, an optimal P regime across varying prices was 32-15 (32 kg P ha^{-1} applied to wheat and 15 kg P ha^{-1} applied to rice). This economic optimum matched all the agronomic criteria for a sustainable P management strategy (Yadvinder-Singh et al 2000).

Applying 32 kg P ha^{-1} to wheat and 15 kg P ha^{-1} to rice was optimal for achieving short-term economic goals and long-term agronomic goals at current yield levels. Although this analysis was restricted to a single-site experiment, it provides a framework for assessing P management strategies for similar studies at other sites. This long-term study also indicated a need to review fertilizer P recommendations at intervals of 5 to 10 years to account for changes in soil P-supplying capacity and the input-output balance.

These component studies have led to the development of a dynamic, site-specific nutrient management strategy for intensive rice-based systems.

Strategies for dynamic, site-specific nutrient management

Quantification of the soil's capacity of supplying N, P, and K is essential to increase yields and nutrient-use efficiencies. Recent on-farm trials in India, Nepal, and Bangladesh have clearly demonstrated that the indigenous supply of N, P, and K under wheat is much smaller than that measured for rice, but is highly variable among farms in both crops (Adhikari et al 1999, IRRI 1999).

Therefore, a new concept and the necessary tools for site-specific nutrient management (SSNM) in rice-rice and rice-wheat systems were developed (Dobermann and White 1999). In the SSNM approach, scientists quantify crop nutrient requirements based on an economically efficient yield target; measure the potential indigenous supply of N, P, and K; estimate the P and K balance for sustaining soil P and K reserves without depletion; monitor plant N status during critical periods of rice growth to optimize fertilizer N efficiency; and apply diagnostic criteria for identifying micronutrient disorders (Dobermann and White 1999, Witt and Dobermann 1999).

The fertilizer recommendation model used is based on the QUEFTS (quantitative evaluation of fertility of tropical soils) model developed at Wageningen (Janssen et al 1990, Smaling and Jansen 1993). Using data collected in on-farm trials under an LTE conducted at eight sites in six countries, we have adjusted the QUEFTS model to model the relationship between grain yield and uptake of N, P, and K by rice (Witt et al 1999) and wheat (C. Witt, unpublished data). A new approach for predicting recovery fractions of P and K fertilizer was developed and incorporated in the model. A critical component of dynamic nutrient management in a site- and season-specific fashion is to regulate the timing of N application based on plant needs. The latter largely depends on variety, climatic factors, and the supply of other nutrients and tends to be highly variable from season to season so that real-time N management is required.

Although much of the early work has been on rice-rice systems, the study also includes rice-maize and rice-wheat systems; thus, the concept is of relevance to rice-wheat systems.

Across 205 rice farms in six countries, results of the first year of field testing showed average yield increases of about 10%. Within one year, average grain yields increased from 5.17 t ha^{-1} (farmers' practice before intervention) to 5.56 t ha^{-1} in the first two rice crops grown with SSNM. Before the introduction of SSNM, only 23% of the farmers achieved yields greater than 6 t ha^{-1}. This proportion increased to 39% in the SSNM plots on the same farms during the first two SSNM crops grown in 1997-98. Compared with the farmers' practice, N-use efficiencies increased by about 40–50% at most sites. Median agronomic N efficiency (AE N) increased from 9.6 kg kg^{-1} (farmers' practice before intervention) to 13.9 kg kg^{-1} in the first two SSNM crops grown. The apparent recovery efficiency of applied N (RE N) increased from 26% to 39%, but was greater than 50% on 25% of all farms (A. Dobermann, unpublished data).

The main factors contributing to this were the improved synchronization between N supply and plant N demand through dynamic adjustment of N doses and more balanced NPK nutrition, including a larger K application. The negative K input-output balance found on many farms was reversed. A preliminary economic analysis shows that, by using existing commercial fertilizers and fertilizer application technology in a site-specific manner, the average farmer's income increased by US$34 per ha per crop in the first year of using SSNM, but by $50 per ha per crop in the second year. Yield and profit increases occurred on about 80% of all farms and the profitability levels achieved should be highly attractive to farmers.

Table 5 and Figure 7 show the specific data for the rice-wheat site at Pantnagar, India. In the first SSNM crop grown (1998 rice), average yield increases of 0.56 t ha^{-1} (10%) were achieved by SSNM at average yield levels of about 6.1 t ha^{-1}. The maximum yield achieved on one farm was 9.3 t ha^{-1}. Similarly, wheat yields increased by 0.56 t ha^{-1} (12%). For both crops, significant increases in N-use efficiency occurred (Table 5). However, a more detailed analysis showed that yields, N efficiency, and nutrient uptake on farms with good crop management were much larger than on one-third of

Table 5. Comparison of site-specific nutrient management (SSNM) and farmers' fertilizer practice (FFP) in 21 farmers' fields at Pantnagar, Uttar Pradesh. Values shown are means of 21 farms sampled in the 1998 kharif rice and 1998-99 rabi wheat seasons (P.P. Singh and A. Dobermann, unpublished data).

Item	1998 Kharif (rice)		1998-99 Rabi (wheat)	
	FFP	SSNM	FFP	SSNM
Grain yield (t ha^{-1})	5.53	6.09	4.82	5.40
Fertilizer N (kg ha^{-1})	125	141	123	108
Fertilizer P (kg ha^{-1})	28	31	21	30
Fertilizer K (kg ha^{-1})	19	44	11	27
Plant N uptake (kg ha^{-1})	109	120	110	127
Plant P uptake (kg ha^{-1})	26	29	23	26
Plant K uptake (kg ha^{-1})	140	153	99	107
Partial productivity of N (kg kg^{-1})	49.5	44.1	41.7	51.1
Agronomic efficiency of N (kg kg^{-1})	12.7	14.4	19.2	26.9
Recovery efficiency of N (kg kg^{-1})	0.49	0.49	0.49	0.69
Physiological efficiency of N (kg kg^{-1})	24.9	29.5	36.1	35.9

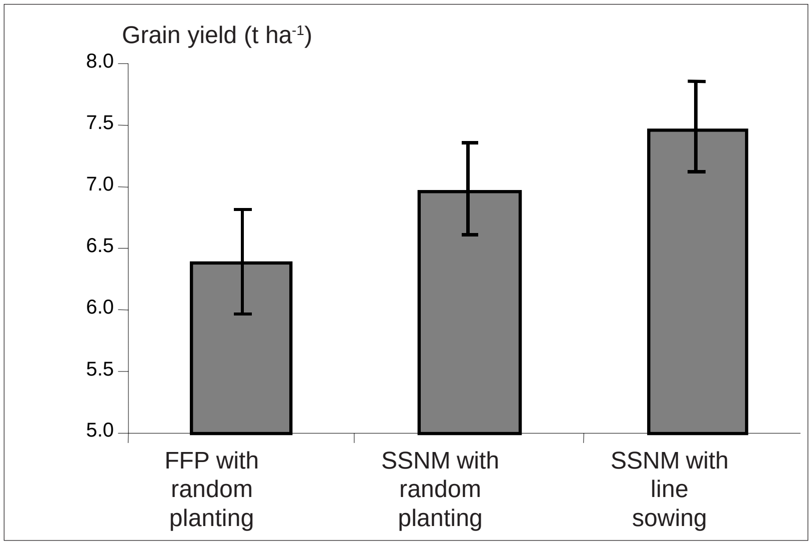

Fig. 7. Rice grain yield in 21 farmers' fields at Pantnagar, Uttar Pradesh, 1999 kharif season. Values shown are means and standard deviations (error bars) of the farmers' fertilizer practice (FFP) and site-specific nutrient management (SSNM) plots (P.P. Singh and A. Dobermann, unpublished data).

the farms with poorly managed fields. This difference was caused mainly by insufficient planting density, indicating scope for further improvement through integrated crop management. High labor costs often cause low planting density when the usual random transplanting method is used. Therefore, in 1999, we added a second SSNM plot to all farmers' fields in which row sowing of rice was practiced to achieve an optimal plant density. Average yields under SSNM with row sowing were 7.5 t ha^{-1} versus 7.0 t ha^{-1} (SSNM) and 6.4 t ha^{-1} (farmers' fertilizer practice) in plots with the normal transplanting method (Fig. 7). These results indicate the enormous potential for increasing yields and nutrient efficiency through a more dynamic, integrated, and site-specific crop management system. Experience from other sites also suggests that the performance of SSNM improves over time, due to both a "learning effect" and gradually improving soil fertility (IRRI 1999).

An outcome of this concept of precision farming is that site-specific knowledge-driven management can be developed for small farmers in Asia and increase farm profits. As the next steps, we will (1) complete the development of essential tools for implementing SSNM at the farm level, (2) do a more detailed agronomic and economic analysis of its performance over time, and (3) start pilot studies on simplifying and extending SSNM to larger areas.

Tillage and crop establishment by nutrient interactions

Tillage, establishment method, and timeliness also affect nutrient management and efficiency. In the Rice-Wheat Consortium, CIMMYT has taken the lead role in the issue of tillage and crop establishment, but links with integrated nutrient management are also needed. In wheat and rice, timeliness of planting is important for optimizing yield.

In rice-wheat systems of South Asia, any delay in wheat planting after the end of November results in a 1–1.5% loss in yield per day delay (Ortiz-Monasterio et al 1994). Late planting can result from the late harvest of the previous crop or the long time needed to prepare a suitable seedbed. To reduce this problem, zero- and reduced-tillage options have been introduced to farmers in the region. These options range from surface-seeded wheat, where no tillage is done, to tillage options involving one pass of a rotovator before sowing wheat. Timing and placement of fertilizer and interaction with water management affect fertilizer efficiency. In zero- and reduced-tillage systems, addition of a fertilizer hopper to the seeder can allow fertilizer placement with a subsequent increase in efficiencies. Where fertilizers are not placed by machinery (surface-seeded wheat), we need to identify the best application strategy to allow maximum efficiency. Data from Pakistan show that, when nitrogen is placed alongside the seed or delayed until the first irrigation in zero-tilled wheat, nitrogen efficiency is similar to that of the conventional system. When the nitrogen is broadcast at seeding on the surface, yields are 19% less (Hobbs et al 1998). Similarly, in surface-seeded wheat, it is better to delay the first nitrogen to the first irrigation since losses of basally, surface-applied nitrogen are high.

Research is also being conducted to evaluate tillage systems for rice and wheat. Direct seeding is an attractive alternative to transplanting of rice to reduce labor input, drudgery in farming, and the cost of cultivation. Rice is direct-seeded either by dry seeding (DSR) primarily in rainfed areas and/or by wet seeding in irrigated areas. Compared with transplanted rice, dry-seeded rice advanced crop establishment by 40–55 days and harvest by 15–30 days, thus allowing timely planting of wheat (Morris 1982). In India and Nepal, experiments evaluated dry-seeded rice with no soil puddling as an alternative to puddled transplanted rice (TPR) followed by zero-till or conventional-tilled wheat (Hobbs et al 2000). Results show that, if rice weeds are controlled, DSR is as good as TPR. Total rice and wheat production was better for DSR followed by a zero-till wheat system. In a study conducted in the Philippines, rice yields were significantly affected by seeding dates, N rates, and their interaction. Rice yields were higher and responded more to N when the crop was planted in June and July than when planted in May (Tuong et al 1995). Direct seeding is constrained by poor water management, stand establishment, and weed control, which need continuing research. Nutrient management, particularly for nitrogen and its interaction with diseases and insects, needs to be examined because sheath blight, blast, and brown planthopper appear to be more prevalent in DSR.

Most of the direct-seeded rice and wheat are planted on flat land and in many cases planting is done in a haphazard way. Wheat, for example, is planted by broadcasting seed and then incorporating it by cultivating. Line sowing by drill is not feasible because of residue problems from the previous crop. Residue management is a major issue in rice-wheat systems. Research has also started on planting wheat on beds rather than on flat land (Sayre and Ramos 1997, Hobbs et al 1998). This opens up many opportunities for improving wheat production, such as the ability to mechanically remove weeds, improve efficiencies in water application, and place topdressed fertilizer and thus increase efficiency. Research shows that similar or even better yields can be obtained with wheat planted on beds because lodging is less and water can be applied at grain filling and more fertilizer can be applied without lodging. It may be interesting to evaluate rice and wheat on permanent bed systems.

The various tillage and establishment options are site-specific. Surface seeding of wheat is being promoted in areas with poor drainage and heavy soils where this system is the only alternative. Zero-tillage with a seed-cum-fertilizer drill is gaining popularity in northwest India and Pakistan, where tractors are available and where reducing production costs is important. Dry direct seeding of rice is suitable in rainfed lowlands, but may also be feasible in irrigated areas with no water constraints (high-water-table Terai areas) or heavy-textured soil areas with poor drainage. Nutrient management and tillage and crop establishment interactions need to be studied in a site-specific context to develop robust nutrient recommendations for new tillage options.

Ecoregional approach to natural resource management

New approaches and methods are being developed for research at the systems level to project future food demand in relation to nutrient management and possible effects on environment. A pilot study in Haryana State of India in rice-wheat systems was conducted taking a broader ecoregional approach. This approach takes into consideration the conflicting interests of industry, urban areas, agriculture, and the environment as agriculture intensifies to meet projected demand. Multiple claims on land and other resources, particularly water and labor, need to be addressed by analyzing options for future land use and natural resource management, taking into account the various productivity, socioeconomic, and ecological goals and aspirations of the community of land users (Roetter et al 1998a,b). For such analyses, new approaches, methodologies, and region-specific toolkits are needed. Land-use planners are interested in models and expert systems to help them make the issues transparent. The complexities of using and managing natural resources need to be examined over space and time.

IRRI's Systems Research Network for Ecoregional Land Use Planning in Tropical Asia (SysNet) aims to develop and evaluate methodologies for exploring land-use options at the subnational level. For this purpose, four regional case studies have been set up: Haryana State (India), Kedah-Perlis Region (Malaysia), Ilocos Norte Province (Philippines), and Can Tho Province (Vietnam) (Roetter and Hoanh 1998).

SysNet

SysNet is a systems research network that develops and evaluates tools and methodologies for exploring land-use options. It was established in 1996 by IRRI and four NARS partners in India, Malaysia, the Philippines, and Vietnam.

SysNet advances and puts into operation land-use analysis methodologies and is going the extra step to ensure that these efforts will have a large impact by getting the tools into the hands of the people who want them. SysNet is training trainers, sharing software for modeling, creating instructional materials, and supporting users by providing access to experts through e-mail and a SysNet Web site.

One of SysNet's case studies is Haryana State (Aggarwal et al 2000). During the most recent stakeholder-scientist workshop for Haryana, held in Delhi in March 1999, various scenarios were formulated and analyzed. Stakeholders had given the following objectives priority:

- doubling of food production for Haryana (tentative goal based on a recent policy statement)
- maximizing agricultural production while setting limits on labor migration—in the future, the supply of labor from outside Haryana may be more restricted
- minimizing nitrogen loss
- minimizing pesticide residues
- improving water management/intervention measures to reduce groundwater depletion
- maximizing income from agriculture

Initial explorations for the scenario "Maximize food production" by the regional optimization model suggest that, with currently available land and water, cereal production could be increased to 16 million t (currently 10.7 million t) if appropriate production technologies were adopted by those farmers who can afford to apply them. Taking actual capital and labor into account as constraints did not change the result, which indicates that water is the most limiting factor. The scenarios assume that improved technologies, which lead to increased fertilizer- and water-use efficiency, can be applied. In the present study, we used five levels of technology that led to different use efficiencies of nutrients. With technology level 5 (N-use efficiency 75% for wheat), the fertilizer requirement (200–250 kg ha^{-1}) and leaching losses of N (10% of applied N) are lower for achieving the maximum attainable (90% of potential) yield, but this requires extra capital for procuring the implements. At the current technology level (N-use efficiency 50% for wheat), however, the existing implements will do, but fertilizer requirements (400–500 kg ha^{-1}) as well as leaching losses of N (25–30% of applied N) will be very high for the same target yield. With current technology (average farmers' practice) and current input use, the model suggested the same food production as what is now being achieved in the state (Aggarwal et al 2000). This shows the potential of the model to develop, analyze, and optimize different scenarios along with their impacts on food production, required resources, production technologies, and environmental consequences to help stakeholders identify feasible solutions and select the best option.

Conclusions and future research agenda

As a member of the consortium, IRRI was tasked by the rice-wheat steering committee to work with NARS and focus on nutrient management of the system, as well as on aspects of characterization, including that of pests. Table 6 summarizes the achievements to date and conclusions drawn from the work, which leads to the development of new objectives for the next phase of the collaborative research.

IRRI, in close cooperation with NARS and IARC partners in the Rice-Wheat Consortium, will continue to pursue a jointly developed long-term strategic research agenda on nutrient management in R-W systems. We will strengthen the holistic and ecoregional research perspectives to (1) understand/quantify SOM and nutrient dynamics, and system interactions, and (2) develop strategies for site-specific integrated nutrient management to manage, preserve, and improve the R-W system's nutrient resource base and indicators to monitor soil quality and sustainability (Fig. 8). The important research issues include

1. Develop a better understanding of the areas and extent of yield declines, stagnating yields, and/or factor productivity declines and yield gaps in rice and wheat, and analyze associated key soil constraints to productivity in R-W systems in South Asia using existing and new methods and models. Relate the geographic occurrence of yield declines and low productivity to agroecological zones, soil type, management practices, input use, and other socioeconomic criteria using GIS.
2. Elucidate the long- and short-term nutrient or SOM processes and dynamics and biological activities that influence the maintenance and enhancement of soil

Table 6. Achievements to date and conclusions drawn for work in rice-wheat systems.

Achievements	Conclusions
Rice-wheat production environments were defined into (1) favorable, predominantly irrigated, and (2) less favorable with predominantly rainfed rice, with irrigated or rainfed wheat.	More detailed agroclimatic analysis would provide an in-depth understanding of the environmental constraints (e.g., drought stress and flood proneness) for geographical targeting of varietal and crop management strategies in both the favorable and less favorable rice-wheat environments.
Using GIS, the rice area (181,000 ha) in Faizabad, a district of eastern Uttar Pradesh, India, was delineated into subecosystems, namely, shallow favorable, shallow drought-prone, and shallow submergence-prone rainfed ecosystems.	The analysis provided insights into developing suitable technologies, such as rice varieties to be developed according to differential growth duration, and crop establishment techniques according to field moisture regimes in different ecosystems. This also provides a methodology for delineating the application domain of promising technologies.
Relationships between rice-wheat cropping practices, biotic constraints, and yields were studied in Uttar Pradesh, India. Six types of disease profiles, four insect injury profiles, and four weed infestation patterns were identified and yield losses were estimated.	The study indicates that IPM recommendation domains and research needs for new IPM strategies can be based on production situations.
The trends in the development of rice-wheat systems, policy issues, and their implications for technology development research were studied.	Agroclimatic (shorter duration of the winter season), physical (heavy soils in floodplains), and technical (lack of irrigation facilities) constraints are more important to the expansion of the system and the growth of productivity than economic factors (unfavorable prices). The findings suggest the need to develop shorter-maturity rice and heat-tolerant, shorter-maturity wheat varieties to expand the system. Further development of irrigation infrastructure may contribute more to expanding the rice-rice system than rice-wheat systems in the eastern part of the Indo-Gangetic Plains.
A study on the role of gender in an unfavorable rice-wheat system in Faizabad, Uttar Pradesh, showed that nonfarm income and livestock are the major sources of household income, and that the labor requirements of rice-wheat production are met mostly by women from the lower social status.	Suggests the need to design cropping patterns wherein the peak of rice-wheat crop management does not conflict with the timing of nonfarm employment, develop varieties with the appropriate quality and quantity of biomass for animal fodder, and increase the participation of farmers (including women) in improving seed selection, storage practices, and cultural management of rice-wheat cropping systems.
A recent analysis of yield trends of several long-term experiments, mostly rice-rice, suggests that yield declines do not appear to be as widespread as once believed, particularly at current yield levels of 5 to 6 t ha^{-1}, whereas, in rice-wheat systems, relatively fewer long-term experiments examined appeared to indicate a yield decline for rice.	There is a need to analyze more longer-term experiments to clarify yield declines in rice-wheat systems.
Detailed analysis of some rice-wheat long-term experiments suggests that mining and changes in availability of nutrients associated with SOM decline are common features that appear to be contributing to the yield decline.	A large database with a wide range of total and biologically active SOM pools from selected long-term experiments and farmers' fields will help in establishing relationships among various SOM quality, soil fertility, and crop productivity parameters, and in clarifying the role of SOM in sustaining crop yields.
Trends in partial factor productivity for fertilizer (PFP-F) can be highly misleading if not interpreted carefully. It is highly preferable to calculate trends in total factor productivity (TFP) or use production functions to assess sustainability. Unfortunately, the data requirements for measuring TFP are much greater than for PFP-F, and not many long-term farm-level data sets have the necessary data.	This work is in the data collection phase of the study at a rice-wheat site in Pantnagar, with the first analysis planned in 2002.

continued...

Table 6 continued.

Achievements	Conclusions
The alternate soil wetting (anaerobic) and drying (aerobic) in the lowland rice system create particular difficulties for N conservation. Soil N mineralized and nitrified at the onset of rains in the fallow may be lost by leaching and by denitrification when the soil becomes submerged for rice.	The extent of N loss in rice-wheat systems and the opportunities to modify cultural practices are areas for further research. It is postulated that the pattern of N and C dynamics and balances in rice-wheat systems is expected to be similar to that of the rice-rice system, and that temperature during the dry season will affect the magnitudes of these processes. Evaluation of diverse crops, particularly legumes, during the dry-to-wet transition in rice-wheat to conserve and recycle soil N is needed.
Fertilizer N-use efficiency of a crop can be increased 30% to 50% by using the chlorophyll meter or leaf color chart, urea deep placement, and controlled-release fertilizers. In rice, these practices have been successfully evaluated and, in some cases, farmers have adopted the leaf color chart and urea deep placement.	The future need is to continue to expand a vigorous on-farm technology evaluation/adoption and economic/impact analysis program in rice, whereas more research is needed in wheat to determine the usefulness of different techniques. In addition, development of a suitable, cost-effective deep-placement machine is urgently needed.
The application of 32 kg P ha^{-1} to wheat and 15 kg P ha^{-1} to rice was optimal for achieving short-term economic goals and long-term agronomic goals at present yield levels. Although this analysis was restricted to a single-site experiment, it provides a framework for assessing P management strategies for similar studies at other sites.	There is a need to review fertilizer P recommendations at intervals of 5 to 10 years to account for changes in soil P-supplying capacity and the input-output balance.
Recent on-farm trials in India, Nepal, and Bangladesh have demonstrated that the indigenous supply of N, P, and K under wheat is much smaller than that measured for rice, but highly variable among farms in both crops. Therefore, there is a need for site-specific nutrient management (SSNM). Following the SSNM concept in several farmers' fields, on an average basis the yields of both rice and wheat increased by 0.6 t ha^{-1} (10%).	An outcome of this concept of precision farming is that site-specific knowledge-driven management can be developed for small farmers, and can increase farm profits. Experience from other sites also suggests that the performance of SSNM improves over time, due to both a "learning effect" and gradually improving soil fertility.
New approaches and methods are being developed for research at the systems level to project future food demand in relation to nutrient management. A pilot study in Haryana, India, in rice-wheat systems was conducted taking into account a broader ecoregional approach and the conflicting interests of industry, urban areas, agriculture, and the environment.	The preliminary analysis suggests that the regional optimization model has potential for predicting different scenarios along with their impacts on food production, input requirements, and environmental consequences to help stakeholders select the best option.

fertility and productivity of R-W systems. Monitor changes in C stocks and flows in rice-wheat cropping systems and identify cultural practices affecting C sequestration in the soil. We will also address the questions (a) Why are the highest R-W yields obtained from the soils with the lowest SOM? and (b) How long can crop production that depends on increasing levels of fertilizer nutrients be sustained?

3. Develop new soil- and plant-based methodologies (static versus dynamic) for better prediction of soil nutrient-supplying capacity that will lead to more knowledge-based fertilizer recommendations.
4. Develop balanced integrated nutrient management strategies that consider (a) crop nutrient requirements for economic yield targets, (b) measurement of potential indigenous nutrient supply and analysis of nutrient balance, (c) diagnosis of micronutrient disorders, (d) and optimization of C management, including integration of legumes and crop residue management.
5. Develop an integrated nutrient management system for new practices such as dry-seeded rice, raised-bed planting of rice and wheat, and zero-till wheat.
6. Develop a nutrient input-output balance at different scales (field/region, short-term/

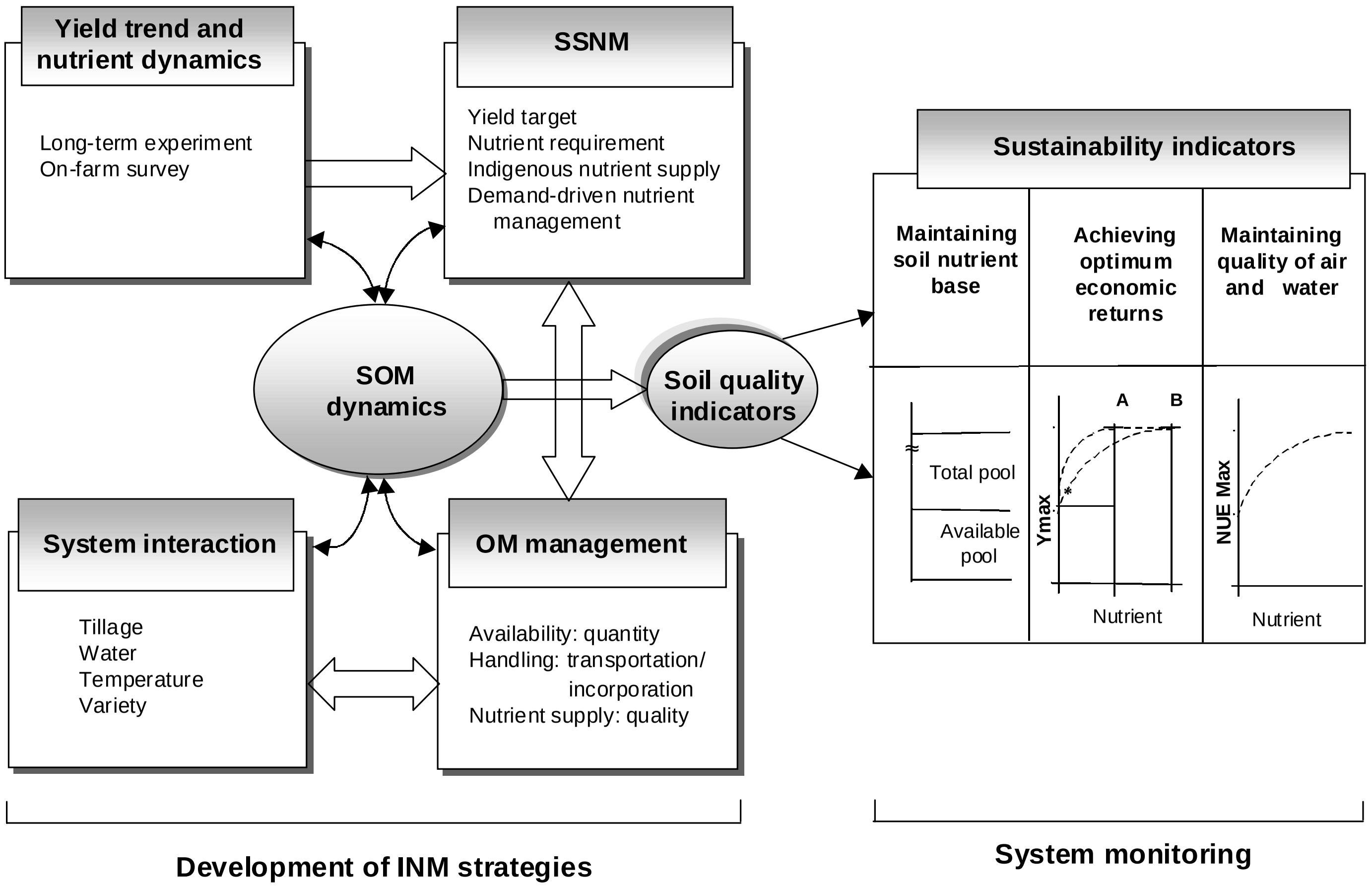

Fig. 8. Nutrient management in sustainable rice-wheat production, a research agenda. SOM = soil organic matter, SSNM = site-specific nutrient management, NUE = nitrogen-use efficiency.

long-term) and optimize different nutrient management scenarios using LUPAS (land-use planning and analysis system) and GIS.

7. Evaluate the influence of weather parameters, crop cultivars, soil properties, and soil management on nutrient supply as well as the interaction of nutrient supply with pests and diseases using simulation modeling.
8. Strengthen the capacity of NARS scientists in soil fertility research through training and collaborative research.

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