Direct Seeding of Rice and Weed Management in the Irrigated Rice-Wheat Cropping System of the Indo-Gangetic Plains

Edited by
Y. Singh, V.P. Singh, B. Chauhan, A. Orr, A.M. Mortimer,
D.E. Johnson, and B. Hardy

Directorate of Experiment Station
G.B. Pant University of Agriculture
and Technology, Pantnagar

IRRI
INTERNATIONAL RICE RESEARCH INSTITUTE
Los Baños, Philippines

The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines . Today, IRRI is one of the 15 nonprofit international research centers supported in part by more than 40 donors: members of the Consultative Group on International Agricultural Research (CGIAR – www.cgiar.org), other government funding agencies, foundations, the private sector, and non-government organizations.

The responsibility for this publication rests with the International Rice Research Institute.

Mailing address: IRRI, DAPO Box 7777, Metro Manila, Philippines
Phone: +63 (2) 580-5600
Fax: +63 (2) 580-5699
Email: irri@cgiar.org
Web: www.irri.org.
Rice Knowledge Bank: www.knowledgebank.irri.org
Courier address: Suite 1009, Security Bank Center
6776 Ayala Avenue, Makati City, Philippines
Tel. +63 (2) 891-1236, 891-1174, 891-1258, 891-1303

Suggested citation: Singh Y, Singh VP, Chauhan B, Orr A, Mortimer AM, Johnson DE, Hardy B, editors. 2008. Direct seeding of rice and weed management in the irrigated rice-wheat cropping system of the Indo-Gangetic Plains. Los Baños (Philippines): International Rice Research Institute, and Pantnagar (India): Directorate of Experiment Station, G.B. Pant University of Agriculture and Technology. 272 p.

Page makeup and composition: Ariel Paelmo
Figures and illustrations: Ariel Paelmo

ISBN 978-971-22-0236-0

Contents

Foreword

The Indo-Gangetic Plains are home to an ancient civilization and the livelihoods of millions of people depend on these fertile plains. With the availability of high-yielding rice and wheat varieties and improved production methods, rice-wheat has become the most dominant cropping system and in irrigated areas double cropping is commonly practiced. In recent years, however, the productivity growth of these two major cereals has been marginal. One major cause of the low productivity of rice is delayed planting caused by various constraints—labor, water, and the power source for transplanting of rice. Alternative technologies of rice establishment—dry and wet seeding—have been developed in a project in operation for the past five years at Pantnagar in collaboration with the International Rice Research Institute (IRRI), Philippines, and Natural Resources Institute (NRI), UK. To take stock of the present knowledge on direct seeding of rice, a workshop was organized at Pantnagar, with participants being scientists from state agricultural universities located in the Gangetic Plains (G.B. Pant University of Agriculture and Technology, Pantnagar; Narendra Deva University of Agriculture and Technology, Faizabad; Chandra Shekhar Azad University of Agriculture and Technology, Kanpur; Rajendra Agricultural University, Bihar), national research institutes (Project Directorate for Cropping Systems Research, Modipuram; Directorate of Rice Research, Hyderabad; Directorate of Wheat Research, Karnal; WTC, Indian Agricultural Research Institute, New Delhi; NRC Weed Control, Jabalpur), IRRI, Los Baños, Philippines; NRI, UK; University of Liverpool, UK; Rice-Wheat Consortium, New Delhi; NGOs; herbicide companies; and farmers of Uttaranchal, Uttar Pradesh, and Bihar. Paper presentations covered the major aspects of rice production—methods of rice establishment, weeds and weed management in different cropping systems, water management, varieties suited to direct seeding, rice quality, and socioeconomic issues. This, I hope, will be of immense help to all stakeholders of direct-seeded rice in the irrigated rice-wheat system and will help promote these technologies, which are cost-effective, save labor and water, and increase farmers' profit.

P.L. Gautam
Deputy Director General (Crop Science)
Indian Council of Agricultural Research

R.S. Zeigler
Director General
International Rice Research Institute

Introduction

Emerging issues and strategies in the rice-wheat cropping system in the Indo-Gangetic Plains

P.L. Gautam

The Indo-Gangetic Plains are the grain bowl of India, occupying 40% of the area and contributing more than 50% to the production of cereals, mainly rice and wheat. The area under the rice-wheat cropping system has increased over the years and, in the state of Punjab, 97% of the cropped area is under these crops only. Production of these two crops has provided food security for India. In the last few years, however, production has stagnated as seen from yield trends, growth rates, and the analysis of long-term experiments. Yields have stabilized at levels much below the potential productivity of existing rice and wheat varieties. One of the major causes of low productivity is delayed planting of rice and wheat in the entire regime, except in Punjab. As one moves east in the Indo-Gangetic Plains, planting gets delayed and yields decline. To overcome the constraints of delayed planting, options are to adopt alternate methods of crop establishment. Technologies are now available for the direct dry seeding of rice, as well as wet seeding, through which the crop can be raised with much less water and energy, and timely planting can be assured. Similarly, zero-tillage and surface-seeding technologies of wheat sowing can advance sowing, reduce production costs, and raise productivity. The other major issue in the Indo-Gangetic Plains is the declining groundwater table because of its overexploitation. In Punjab, 66% of the area is well irrigated. In Uttar Pradesh, 75% of the irrigation is from wells. Recharge of groundwater through monsoon irrigation is the best option to conserve water for double cropping and reduce the cost of pumping the water. Water-use efficiency can be enhanced by alternate ways of irrigation scheduling in dry and wet regimes or aerobic cultivation. Laser leveling, integrated nutrient management, and integrated pest management can improve water-use efficiency. The present practices of burning up residues leads to a loss of carbon and machines are needed to incorporate or better retain the residues for surface decomposition to add nutrients and improve soil biological activity. Better nutrient management can be achieved through site-specific nutrient management. To raise farm income and sustainability of the system, system diversification has been recommended.

Table 1. Shift in cropping pattern and food grain production in Punjab.

Years (TE)[a]	Total area of food-grain crops (million ha)	Share (%) in total cropping pattern				Total food-grain production (t)
		Rice	Wheat	Coarse cereals	Pulses	
1971-72	3.9	10.5	58.0	20.4	11.2	6.8
1984-85	5.2	28.5	59.5	8.1	3.9	15.0
1995-96	5.9	37.8	57.9	3.6	0.8	21.1
2000-01	6.2	41.8	54.7	3.2	0.3	25.0

[a]TE = triennium ending.
Source: Janaiah and Hossain (2003).

The Indo-Gangetic Plains (IGP) are home of an ancient civilization and archeological evidence of the same is seen in Mohanjodaro and Harappa in Punjab of Pakistan and Nalanda in Bihar, India. These are considered as the most fertile plains and the livelihood of millions of people depends on the agricultural richness of these lands. In the past, based on natural resources, the western part of the IGP (Punjab and western Uttar Pradesh) was an important wheat-producing area, whereas the eastern part (eastern Uttar Pradesh, Bihar, West Bengal) was mainly a rice-producing area. With a need to produce more and the development of infrastructure, irrigation, fertilizer, and improved seeds, rice cultivation was extended in the western areas and wheat toward the east, making the IGP an important rice-wheat area. The main thrust came during the Green Revolution era with the availability of high-yielding short-duration photo-insensitive varieties and modern technologies for rice and wheat production, which made rice-wheat double cropping possible. This brought a significant change in the cropping pattern and cropping intensity in the entire IGP. A marked example of this shift can be seen in the state of Punjab, where 97% of the cropped area is under rice and wheat (Table 1).

Rice-wheat has emerged as the most widespread crop production system in the IGP and the national rice-wheat area is estimated to be around 10 million ha (Paroda et al 1994, Hobbs and Morris 1996, Yadav et al 1998, Ladha et al 2000, Timsina and Connor 2001, Gupta et al 2003). The major states in the IGP are Uttar Pradesh, Bihar, Punjab, and Haryana (Woodhead et al 1994). Other states having a small rice-wheat area are Uttaranchal, Madhya Pradesh, Rajasthan, Himachal Pradesh, and the Brahmaputra flood plains of Assam. Spatial variation is large in physiographic, climatic, edaphic, and socioeconomic features of the IGP. The western part of the IGP has a semiarid climate, with annual rainfall of 500–800 mm, whereas the eastern part (eastern Uttar Pradesh, Bihar, and West Bengal) experiences a humid climate with annual rainfall of 1,000–1,200 mm. The summer and winter temperatures are extreme in western IGP, whereas, in the eastern part, they are moderate. Soils are mostly Inceptisols. Considering agro-climatic conditions, crop duration, and infrastructure, the western part of the IGP (Punjab, Haryana, and western U.P.) is considered a favorable environment for rice-wheat, whereas the eastern part is considered unfavorable.

Increased area under rice-wheat double cropping and the increasing productivity of these crops have made India self-sufficient, but at the same time this made food security highly dependent on the performance of these two crops. During the Green Revolution years, the growth rate of wheat (3%) and rice (2.3%) was higher than population growth and thus production was in surplus. But, during the 1990s, with the onset of second-generation problems such as soil fatigue caused by intensive cultivation and negative nutrient balance, a continuous decrease in input-use efficien-

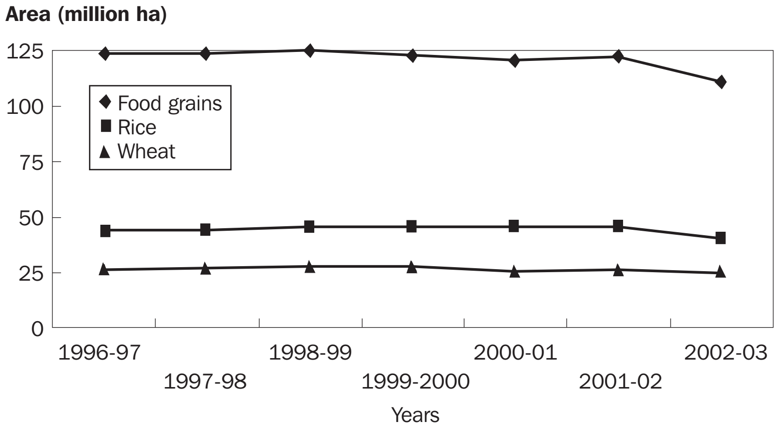

Fig. 1. Area under rice, wheat, and total food grains in India.

cies, and a declining water table, the production and productivity gains of these two crops and also that of total food grains, particularly in the high-productivity states of Punjab and Haryana, are slowing. Because of population pressure, good lands are being diverted to other uses and prospects for further expansion of rice and wheat area seem remote (FAO 1999). Additional sources of productivity growth in rice-wheat would have to come through newer technological interventions that enhance overall system productivity.

Yield stagnation

The trends in productivity and production of rice and wheat show a reduced growth rate, stagnation, and even a decline in some cases. This can be seen from short- and long-term productivity trends, potential yield and yield gap analysis, results of long-term experiments, and temporal variations in total factor productivity.

Trends in area production and productivity

The productivity of rice and wheat, which constitute 80% of total food grains, has been nearly stagnant for the last few years (Figs. 1, 2, and 3). Wheat yields have been oscillating around 2.0 t ha^{-1} and rice at 2.7 t ha^{-1}. Yield stagnation has occurred at productivity levels that are much lower than the genetic potential of the varieties. Further, the yield plateau has been reached in the high-potential areas of Punjab, Haryana, and western Uttar Pradesh. Since the area under these crops has nearly stabilized, production has also become stagnant. This is a major concern. While from 1999 to 2003 the population grew from 996 to 1,068 million, that is, a 7.2% increase or nearly 2% annual increase, production remained around 210 million t in 1999. The International Food Policy Research Institute in Washington, D.C. (USA), developed an International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), which has predicted that South Asia would end up in deficit in producing its main food grains, rice and wheat. According to World Watch estimates also, India may be importing a substantial amount of food grains by 2025 (Tiwari 2002).

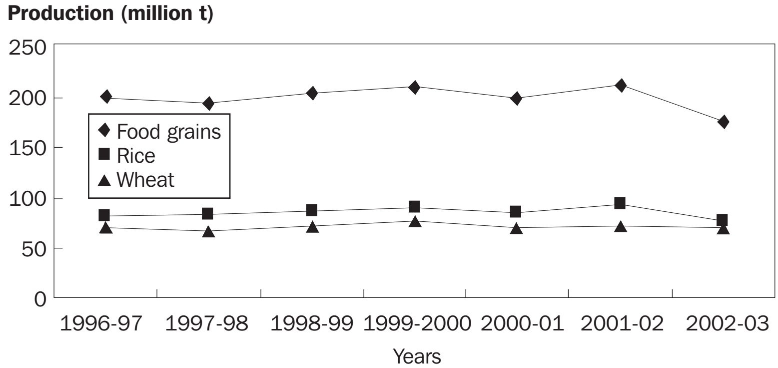

Fig. 2. Production of rice, wheat, and total food grains in India.

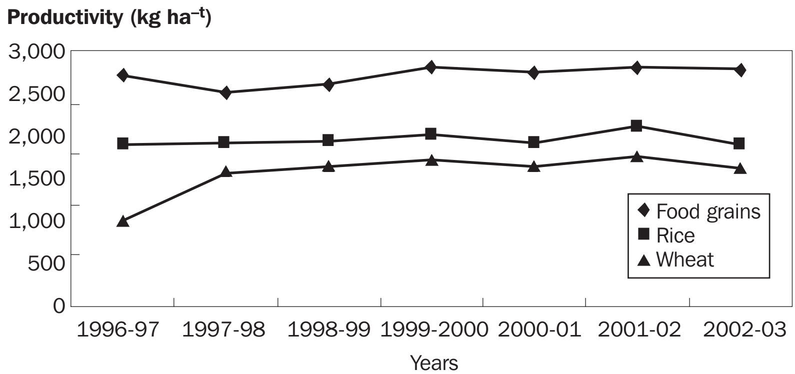

Fig. 3. Productivity of rice, wheat, and total food grains in India.

Long-term productivity trends

An assessment of long-term productivity trends in the IGP shows that the productivity growth of rice in farmers' fields has declined (Table 2) yet no yield decline occurred in absolute terms (Janaiah and Hossain 2003). On the other hand, wheat yield increased at 1.8–2.6% per annum in the late Green Revolution period and this increase has sustained the system's productivity.

Productivity in long-term experiments

In the 1990s, concern was raised among the scientific community regarding the declining trend in rice-wheat productivity. It started with observations of declining yield trends in rice in cultivar trials at IRRI under the rice-rice system (Ponnamperuma 1979). To pursue this hypothesis of yield decline, data of many long-term experiments (LTE) in South and Southeast Asia under rice-rice and rice-wheat systems were analyzed by a group of scientists (Flinn and De Datta 1984, Cassman and Pingali 1995, Yadav et al 1998, Brar et al 1998, Aggarwal et al 2000, Dawe et al 2000, Duxbury et al 2000). In some of these trials, declining rice and wheat yield were reported, whereas, in others, yields either increased or were maintained. Overall yield declines were not common and the decline was more in rice than in wheat. Recently, Ladha et al (2003) and Padre and Ladha (2004) analyzed the yield trend in LTE using a linear mixed effect model and meta analysis. Results from

Table 2. Change in productivity of rice and wheat in India.

State and crop	Yield (t ha^{-1})				% change in yield		
	1971-72 (TE)[a]	1984-85 (TE)	1995-96 (TE)	2000-01 (TE)	1984-85 over 1971-72	1995-96 over 1984-85	2000-01 over 1995-96
Punjab							
Rice	1.8	3.1	3.3	3.4	75.3	8.1	0.3
Wheat	2.3	3.1	4.0	4.6	35.7	28.5	15.8
Haryana							
Rice	1.7	2.5	2.6	2.4	43.4	2.7	–8.5
Wheat	2.1	2.5	3.7	4.1	22.9	44.4	12.6
Uttar Pradesh							
Rice	0.8	1.2	1.9	2.1	54.5	52.5	10.0
Wheat	1.2	1.9	2.4	2.7	50.5	29.9	17.2
Bihar							
Rice	0.8	0.9	1.3	1.5	9.6	45.1	18.6
Wheat	1.3	1.5	2.1	2.2	20.6	35.3	6.8
West Bengal							
Rice	1.3	1.6	2.1	2.3	22.3	32.7	12.6
Wheat	2.1	2.4	2.3	2.4	16.6	–4.6	2.6

[a]TE = triennium ending.
Source: Janaiah and Hossain (2003).

the two models were in agreement. The linear mixed effect model showed a significantly declining rice yield trend at the IGP sites (–37 kg ha^{-1} y^{-1}). The significant decline was at 8 out of 17 sites. Similarly, meta analysis showed a significantly negative correlation between rice grain yield and number of cropping years for LTE at the IGP sites (Fig. 4). Wheat yields remained stable. As a consequence, change in the system yield (rice + wheat) was not significant. The aggregate analyses also showed that the combination of an inorganic (NPK) and organic source (farmyard manure, FYM) can arrest the yield decline of rice in the rice-wheat system. A linear response of rice and wheat yield to an increasing amount of NPK was observed in a majority of 12 LTEs during the initial and final 3 years of the experiment, indicating that both rice and wheat yield could still be increased with higher nutrient inputs. The possible causes of yield stagnation or decline have been suggested as decreased soil carbon, nutrient depletion and imbalances, changes in soil properties, climatic changes, and pest problems.

Decline in total factor productivity

A study of total factor productivity (TFP) of the crop sector in the Indian part of the IGP was done by Kumar (2003). The study revealed that TFP for rice and wheat crops increased during the 1970s. During this period, TFP growth was higher for rice than for wheat and later it was vice versa. During the 1980s, TFP was higher than in the 1990s. In 1981-90, 42% of the gross cropped area (GCA) recorded the highest TFP growth of 2% and this area declined to 14% during 1991-96. The area under moderate TFP also declined, while the area under low TFP growth increased. During the 1990s, TFP in 39% of GCA was stagnant and it declined in 23% of GCA. Indiscriminate groundwater use without provision of recharge and declining biodiversity have severely affected TFP growth in Punjab and Haryana. The breaking of the current irrigated yield ceiling for rice and wheat is necessary to maintain system sustainability.

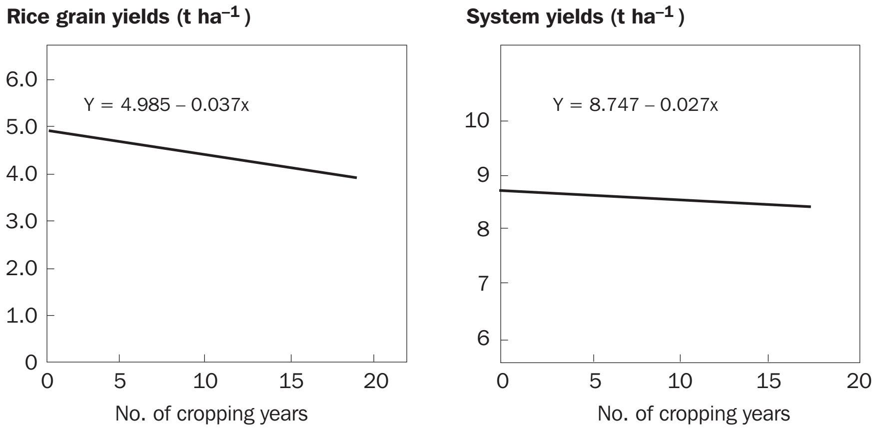

Fig. 4. Aggregate yield trends in rice and system yield (rice + wheat) in long-term experiments in the rice-wheat cropping system in the Indo-Gangetic Plains.

Potential yield and yield gap

Potential yield for rice and wheat for different sites in the IGP has been worked out using available models (Singh et al 1998, Aggarwal et al 2000). These yields decrease toward the eastern region of the IGP because of lower solar radiation and high daily minimum temperature in the lower part of the IGP resulting in decreased photosynthesis, increased respiration, and a shortened vegetative and grain-filling period (Yoshida and Parao 1976, Penning de Vries 1993, Horie et al 1995).

The yield gap between potential and experiment station yield was 35% to 55% for rice and 25% to 46% for wheat. There are large gaps between potential and farmers' actual yields and these ranged from 48% to 71% for rice and 35% to 60% for wheat (Table 3). In Punjab, at Ludhiana, there is no yield difference in rice yield on the experiment station and in farmers' fields and the same is the case at Pantnagar for wheat yield. In the rest of the cases, there is a big gap (22–44% for rice and 7–39% for wheat) in yield between the experiment station and farmers' fields. This suggests a tremendous scope for improving yield with improved crop management by increasing input use and its use efficiency to close the yield gap. Swaminathan (2003) has considered this untapped production reservoir existing on our farms a major potential economic asset.

Crop establishment—delayed planting of rice and wheat

Late planting is a major problem in most rice-wheat areas except Punjab (Fujisaka et al 1994), where rice is transplanted in late May and June and wheat sown in November, the best time to harvest maximum yield (Fig. 5). Moving east, planting gets delayed and most of the rice in Uttar Pradesh and Bihar is transplanted in July and planting continues till mid- or even late August. This in turn delays wheat sowing and surveys in Haryana and Uttar Pradesh have shown that more than half of the wheat area is sown in December (Hobbs et al 1991, 1992, Harrington et al 1993). In Bihar, most of the wheat area is sown in December and this is one of the major causes of low productivity of the two crops. In Punjab, where timely planting is done, productivity of the two crops is highest.

Numerous sowing-date experiments in the Indo-Gangetic Plains have shown that rice planted in June and wheat in November gave the highest productivity, and delay in sowing brought a linear

Table 3. Potential, on-station, and on-farm yields and the yield gap of rice and wheat in different zones of the IGP.

Site	Rice						Wheat					
	Potential yield (A) ($t\ ha^{-1}$)	On-station yield (B) ($t\ ha^{-1}$)	On-farm yield (C) ($t\ ha^{-1}$)	Yield gap %			Potential yield (A) ($t\ ha^{-1}$)	On-station yield (B) ($t\ ha^{-1}$)	On-farm yield (C) ($t\ ha^{-1}$)	Yield gap %		
				$\frac{(A-B)}{A} \times 100$	$\frac{(A-C)}{A} \times 100$	$\frac{(B-C)}{B} \times 100$				$\frac{(A-B)}{A} \times 100$	$\frac{(A-C)}{A} \times 100$	$\frac{(B-C)}{B} \times 100$
Ludhiana	10.7	5.6	6.5	48	48	0	7.9	4.7	4.3	41	46	9
Karnal	10.4	6.8	3.8	35	63	44	7.3	4.6	3.6	37	51	22
Kanpur	9.5	4.5	2.8	53	71	38	7.0	4.6	2.8	35	60	39
Pantnagar	9.0	5.5	4.2	39	53	24	6.5	3.9	4.2	40	35	–
Varanasi	9.2	4.1	3.2	55	65	22	7.0	3.8	3.2	46	54	19
Faizabad	9.1	4.2	2.8	54	69	33	6.7	3.4	2.8	49	58	18
24-Pargana	7.7	4.4	2.8	43	64	36	5.2	3.0	2.8	43	46	7

Source: Ladha et al (2003).

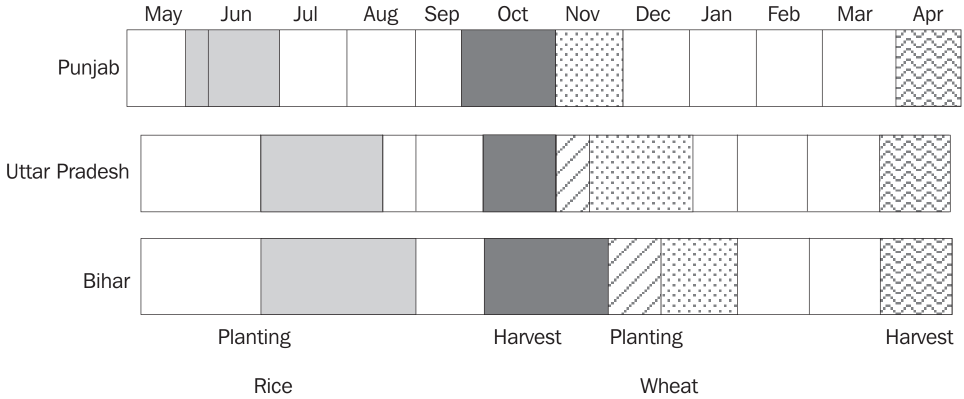

Fig. 5. The rice-wheat calendar in Punjab, Uttar Pradesh, and Bihar.

decrease in yield. Estimates show a 1–1.5% wheat yield decline per day (Ortiz-Monasterio et al 1994, Randhawa et al 1981, Hobbs and Mehla 2003) or a decrease of 47 kg per day per hectare in December and 57 kg per day per hectare in January (Misra 2003). The decline in rice yield beyond June transplanting is higher still (Lal 1985). In addition to yield decline, delayed planting also reduces the efficiency of input use (Hobbs and Gupta 2003). Losses because of delayed sowing of wheat cannot be overcome by additional nitrogen (Saunders 1990). To raise the productivity of the two crops, these must be planted in time and constraints that delay planting must be removed. The main constraints to timely planting of rice are uncertainty of rains, lack of irrigation facilities and the high cost of pumping water, transplanting that requires a lot of water and labor and high wages, and the shortage of labor during the peak transplanting period. The obstacles to timely wheat sowing are delayed rice harvesting, long-duration varieties, excessive or too little soil moisture, many tillage operations done in puddled rice fields with degraded soil physical conditions, and limited farm power. The problems in late planting of both rice and wheat can be solved through alternate methods of crop establishment.

Direct seeding of rice

Transplanting is the dominant method of rice establishment in the rice-wheat growing areas of the IGP and in all Asia. However, economic factors and recent changes in rice production technology have improved the desirability of direct-seeding methods (Pandey and Velasco 2005). Accordingly, there has been a rapid shift to the direct-seeding method of rice establishment in Southeast Asia. The economic impact of the spread of direct seeding has been positive overall. The major forces driving the spread of direct-seeding methods are the availability of chemical methods of weed control, the increasing scarcity of water and its rising cost, and less availability of farm labor. Direct seeding of rice in the IGP has begun and farmers are finding the new technology attractive. The productivity of the direct-seeded crop is on a par with transplanting and the net profit higher (Singh et al 2005).

There are alternate methods of direct seeding—wet and dry. In wet seeding, fields are puddled and sprouted seeds are sown on the puddled bed using a drum seeder, or just broadcasting 50 kg of seed per hectare is sufficient. Wet seeding saves labor cost, drudgery is reduced, and the main advantage is that the crop can be established in time and a better crop stand can be achieved (De Datta 1986, De Datta and Flinn 1986). Good land preparation and leveling and effective weed control are critical for the success of wet-seeded rice (Balasubramanian and Hill 2002). A perfect stand can be achieved on laser-leveled fields.

In dry seeding, rice is sown after field preparation at optimum moisture for seed germination. The fields are prepared in June and the crop sown with presowing irrigation to establish it before the onset of monsoon. This method ensures timely crop establishment, which will result in increased productivity. With the same available farm power and labor, much more area can be sown in much less time by direct drilling. There is a savings of water required for puddling. Nitrate accumulated in the soil during the dry fallow period will not be denitrified because of the absence of early flooding in nonpuddled soil. Nutrient dynamics would be different in most aerobic soil. Such fields would be intermittently flooded by rains. Zero-tillage sowing of rice after wheat is also showing promise in IGP conditions (Singh 2005). By adopting any of these direct-seeding technologies, rice establishment can be timely as these methods require less labor, water, and energy. This is likely to increase rice productivity, which is much below the potential yield.

Zero-tillage and surface seeding of wheat

Traditionally, wheat after rice is sown after thorough field preparation, which involves up to 6–8 harrowings/cultivations and 2–3 plankings. This delays wheat sowing and increases production costs. Wheat sowing can be advanced and timely sowing done by avoiding tillage operations or using zero-tillage. The zero-tillage system refers to sowing of the crop with a minimum of soil disturbance. Sowing is done without any prior tillage operation after the rice harvest. In undisturbed soil, macro- and micro-fauna build up and maintain an open-pore structure of soil. The presence of residues on the soil surface conserves soil moisture and also serves as a source of energy for soil life for bio-tillage (Gupta et al 2003). Weed emergence, particularly of *Phalaris minor*, is much less under zero-tillage (Verma and Srivastava 1989, 1994, Singh 1995). Zero-tillage results in higher yields because of timely sowing, better crop stand, and increased input-use efficiency (Aslam et al 1993, Malik 1996, Hobbs et al 1997, Abrol et al 2000, Tullberg et al 2001, Hobbs and Gupta 2003). The cost savings is on the order of US$50–70 ha^{-1}. Zero-tillage saves water and wear and tear on tractors, promotes residue management, and helps to reduce air pollution. The advantages of zero-tillage are more in areas where wheat is traditionally sown late in the eastern IGP. Farmers who have adopted zero-tillage and practiced it for 4 years find no deleterious effects (Malik et al 2002).

Combine harvesting of wheat is becoming popular in the IGP, particularly in the western part. In combine harvesting, loose straw and residues are commonly left after harvest. The current zero-tillage drills do not work efficiently with loose straw on the soil surface as the drills rake and collect the straw, which hinders their operation. To overcome this problem, farmers burn the residues, which is not desirable for the environment. Efforts are being made to develop an alternate drill with disc openers. Leaving the straw mulch on the surface is beneficial to the establishment and vigor of the crops planted this way (Sayre 2000). Hence, much attention is required to develop technology and a machine to seed the crop with residues left on the surface.

In the eastern IGP, where drainage is poor, the soil remains wet for a long time, thus delaying wheat sowing. In these soils, surface seeding of wheat can be practiced (Hobbs et al 2003). In this technique, presoaked seeds are either broadcast or drum-seeded on saturated soils. This allows wheat crops to be sown in fields that would have otherwise remained fallow during the rabi (winter) season or rabi crops—wheat, chickpea, lentil, or lathyrus—would have been planted very late.

Water crisis

Water resources are under severe pressure. In the western IGP, dependence has been increasing on groundwater for irrigation. Presently, two-thirds of the area in Punjab is irrigated by wells while for Uttar Pradesh it is 75%. Because of the overexploitation of groundwater, the water tables are getting deeper, well discharges have decreased, and pumping cost increased. According to the Consultative Group on International Agricultural Research–Challenge Program on Water and Food, increasing water scarcity and competition for the same water from nonagricultural sectors point to an urgent need to improve crop productivity to ensure adequate food for future generations with the same or less water than is presently available (www.waterforfood.org). In Asia, irrigated agriculture accounts for 90% of the total diversified fresh water used, and more than 50% of this is used to irrigate rice. Rice requires from 1,000 to more than 3,000 L of water to produce each kg of rice (Cantrell and Hettel 2005). In India, around 80% of the fresh-water resources are used in agriculture. It is estimated that availability of water for agricultural uses may decrease by 21% by 2020 and crops such as rice may suffer. Under traditional practices in the tropics and subtropics, rice requires 7,000–15,000 m^3 water ha^{-1}. This consists of 150 to 250 mm for land preparation, 50 mm for growing rice seedlings, and 500–1,200 mm to meet evapo-transpiration (ET) demand and seepage losses, excluding rainfall (Guerra et al 1998). Such quantities of water may not be available in the future and thus strategies are required to conserve more water, improve the delivery systems, and produce more from each unit of water.

Water conservation

In the western part of the IGP, from annual rainfall of 650 to 1,000 mm, only 200 mm of water percolates to recharge underlying aquifers (Sakthivadival and Chawala 2003). Most of this rainfall, which is concentrated in monsoon months, is not absorbed into already saturated soil and runoff flows unused to the sea. If part of it is conserved, water resources could be greatly augmented. Building surface storage dams is not an option in the flat alluvial terrain of the IGP. The best and most cost-effective way is to store this water underground through artificial recharge, for which the hydrological conditions in the IGP are very conducive. This will solve the problem of declining water tables.

Recent research done by Roorkee University, the Water and Land Management Institute (WALMI) of Uttar Pradesh, and the state's irrigation department in collaboration with the International Water Management Institute (IWMI) suggests that providing farmers with irrigation water during monsoon offers a cost-effective option to harvest water and to recharge groundwater (Sakthivadival and Chawala 2003). The study in the Madhya Ganga Canal area (Lakhaoti Branch Canal System) has shown that providing irrigation water in the monsoon season has affected groundwater level, land use, cropping pattern, and cost of pumping water. The research showed that the water table, which had been progressively declining, has been raised from an average of 12 m below ground level in 1988 to an average of 6.5 m in 10 years. Without this intervention, the water table would have fallen to 18.5 m during the decade. The recharged aquifers also provide water for the next rabi crop and for domestic and industrial uses. Providing canal water during the monsoon season has several other advantages. Farmers are not at the mercy of monsoon and can harvest good rice and wheat crops. The cost of pumping water from 6.5-m depth was Rs. 0.265 m^{-3} versus Rs. 0.465 m^{-3} for water from 18-m depth.

The most effective way to recharge groundwater is to modify the operation of the irrigation system to carry surplus monsoon flows. Drains with proper structures can be used for recharging groundwater. A strategy of combining groundwater recharge with appropriate pricing and groundwater regulation has the potential to improve productivity and sustainability of groundwater use in areas where excessive pumping is endangering groundwater resources. This will require certain policy changes and initiatives.

Increasing on-farm water productivity

Increasing agricultural output with the same amount of water is a key strategy for overcoming water scarcity. This may involve three areas:

Improving irrigation scheduling. Two types of water-saving systems can be used to replace the traditional irrigated rice production systems. One is alternate wetting and drying in which the field is irrigated with enough water to flood the paddy for 3–5 days, and, as the water is soaked into the soil, the surface is allowed to dry for a few days (usually 2–4) before getting reflooded (Hatta 1967, Prihar and Grewal 1985). Another alternative is aerobic rice, in which the rice is sown directly into the dry soil, like wheat or maize, and irrigation is applied to keep the soil sufficiently moist. Both of these systems allow for substantial water savings of 30–50% (Cantrell and Hettel 2005). At Ludhiana, Sandhu et al (1980) observed that delaying irrigation for 1–5 days after the disappearance of ponded water in a sandy loam soil brought about no significant reduction in rice yield. Bhuiyan (1992) reported a 40% savings in water without yield loss by replacing shallow-depth water regimes with a saturated soil regime in puddled transplanted rice.

Crop substitution and changing crop varieties. By switching over from high water-consuming crops to less water-consuming crops, or switching to crops with higher economic or physical productivity per unit of water consumed, there can be savings of water and the profit earned by farmers can be enhanced. Rice varieties are also being identified that perform better under water-stress conditions and these varieties can produce the same yield with much less water.

Improving crop management. Agronomic practices such as land leveling and alternate methods of crop establishment can lead to savings of water, and optimum fertilizer use can enhance productivity and raise water-use efficiency. By dry seeding rice, water used for puddling can be saved, but deep percolation losses may increase in nonpuddled soil. But, this water remains in the system and can be recycled. Precision leveling by a laser leveler has shown improved water management, crop stand, and productivity in direct-seeded rice (Hill et al 1991, Bell et al 1998, Rickman et al 1998). In Pakistan, laser leveling has reduced water use by 50% in irrigated rice, facilitated germination and crop establishment, and increased yield by as much as 25% (Balasubramanian et al 2003). Kahlown et al (2000) observed that laser leveling improved crop performance in nonpuddled soil with zero-till surface seeding or seeding on permanent beds. Water productivity was also better in laser-leveled, zero-till, and bed-planted wheat than with conventional tillage. Planting rice on raised beds can save up to 50% water (Connor et al 2003).

Crop residue management

Crop residues are potential sources for improving soil organic matter dynamics, nutrient recycling, and the soil physical environment. With increased production of rice and wheat, straw production has also increased, and the estimated amount of rice and wheat residues produced in India is 113.6 million tons (Sarkar et al 1999). Traditionally, rice and wheat were harvested manually and straw was used for cattle feed. In the last decade, the use of combine harvesters has been increasing. According to a survey conducted in Punjab, 91% of rice and 82% of wheat area are harvested by combines (ICAR 1999). The combine harvester leaves the straw residue on the field surface and farmers are not equipped to handle such a large mass of residues left in the field; hence, most farmers burn the residues. This is a serious waste of precious nutrient resources and contributes to

Table 4. Estimated loss of nutrients caused by burning of crop residues in the rice-wheat system.

Straw	Nutrient content ha^{-1}			Estimated loss					
	N	K	S	kg ha^{-1}			%		
				N	K	S	N	K	S
Rice	48.0	104.8	8.0	42.8	20.8	2.0	89.2	19.0	25.0
Wheat	40.0	92.0	9.6	35.4	16.0	2.4	88.5	17.4	25.0

Source: Sharma (1998).

Table 5. Greenhouse gas emissions (CO_2 equivalent) from burning of rice straw in northwest India (in Tg).

State	CO_2	CO	CH_4	N_2O
Punjab	13.60	0.869	0.047	0.175
Haryana	1.56	0.099	0.005	0.013
Uttar Pradesh	11.10	0.706	0.038	0.090
Total	26.26	1.674	0.090	0.278

Source: Samra et al (2003).

intense air pollution. Studies at Pantnagar have shown a major loss of nitrogen in straw by burning (Table 4).

Burning of rice straw causes gaseous emissions of 70% CO_2, 7% CO, 0.66% CH_4, and 2.09% N_2O. Estimates of these gaseous emissions in three states of the IGP are given in Table 5.

The incorporation of crop residues alters the soil environment, which in turn influences microbial population activity in the soil and subsequent nutrient transformation (Kumar and Goh 2000). A major problem encountered in the use of rice and wheat residues is the occurrence of the microbial immobilization of soil and fertilizer N in the short term (Mary et al 1996). A crop grown immediately after the incorporation of residues suffers from N deficiency. An addition of N fertilizer along with residue could only partly offset the immobilization process. Allowing adequate time for the decomposition of residues before planting the next crop can be beneficial. Recycling of rice residues poses more problems than wheat straw because of the short gap between rice residue incorporation and wheat sowing, low temperature, and the slow rate of decomposition of rice straw.

Research on rice-wheat residue management has focused more on the effects of residues on soil properties; the partial substitution of nutrients, particularly nitrogen, by the residues; nitrogen immobilization by increased soil carbon content; and crop yields. Beneficial effects of residues have been observed in the long term. However, no suitable technology has been developed locally by which farmers can incorporate residues with less energy/cost or residues can be allowed to stay on the field surface and the next crop can be sown in the stubbles. New planters with disc openers are being evaluated for this purpose (Gupta and Rickman 2002). Other options include baling of straw and use in industry and animal feed (Thakur 2003). Adoption of such alternatives will avoid burning of residues.

Nutrient mining and imbalances

Rice and wheat are heavy users of nutrients and nutrient imbalance and soil mining by these cereals have led to nutrient deficiencies and poor soil quality. Presently, in India, against crop removal of 28 million t of nutrient (NPK), the addition of only 18 million t of these nutrients in fertilizer results in a deficit of nearly 10 million t. Average annual nutrient use in India is around 100 kg (NPK) ha^{-1} compared with 271 kg ha^{-1} in China and 459 kg ha^{-1} in Korea (Pathak et al 2002). The regional distribution of fertilizer is also not uniform. Whereas farmers in Punjab use 250 kg nutrient ha^{-1}, use in the eastern region is much less. Further, continuous rice-wheat monoculture without break crops, the decline in soil organic matter, residue burning on an increasing scale, and intensive mining of surface soil because of the restricted rice-wheat root zone are affecting nutrient availability to these crops. Results of long-term experiments show a linear response to applied nutrients, suggesting scope for higher applications (Ladha et al 2003). Zn deficiency in the IGP is widespread and Nayyar (2003) reported that, through the analysis of 90,218 samples of the IGP, zinc deficiency was noted in 54%, 60%, 48%, 45%, and 36% of the samples from Bihar, Haryana, Punjab, Uttar Pradesh, and West Bengal, respectively. Against this magnitude of deficiency, the use of zinc fertilizers is very limited. Now, in several areas, deficiencies of other micronutrients—Fe, Mn, Cu, and B—are appearing, about which farmers are not aware. The micronutrient requirement of rice is more than that of wheat.

Presently, only general fertilizer recommendations by different states are available, whereas soil nutrient supply varies greatly from field to field and sometimes even within a field (Dobermann et al 1996, Dobermann and White 1999). Further crop requirements for nutrients vary with sowing time, season, location, field history, and growing conditions. In Punjab, in the rice-wheat system, farmers apply more P fertilizer to wheat, which has resulted in an accumulation of P in soils. Thus, site-specific nutrient management (SSNM), which takes the above factors into consideration, needs to be practiced to provide balanced and optimum nutrient use. Use of the chlorophyll meter and leaf color chart is being recommended to decide the rate and time of N application (Balasubramanian et al 1999, 2000, Peng et al 1996, Turner and Jund 1994). For P and K management, nutrient omission technology is suggested (Dobermann and Fairhurst 2000). This technique determines the soil-supplying capacity of and crop requirement for P and K in individual fields. SSNM raises crop productivity and nutrient-use efficiency, thus adding to the profit of farmers.

Profit margin—diversification of the rice-wheat system

The economic factors of rice and wheat cultivation in India have been studied by Singh and Chandra (2002). In these crops, the growth rate in the support price has been less than the growth in cost of cultivation (Table 6). The margin of profit in relation to the total cost of cultivation is very low and the margins are declining. This discourages farmers from investing more to increase productivity.

The decline in the real price of rice and wheat and also their unit production cost was reported earlier by Kumar (1997), and the price of rice in the world market has been declining in real terms since 1975. The declining trends in the global prices of agricultural commodities, especially food grains, endanger the sustainability of the majority of the farmers who depend for their food security on small farm holdings (Joshi 2003). Globalization is a new challenge that may threaten the viability of rice-wheat farm holdings where yields are low. The remedy lies in raising rice and wheat productivity and producing the same or more grain on a part of the holdings and sparing

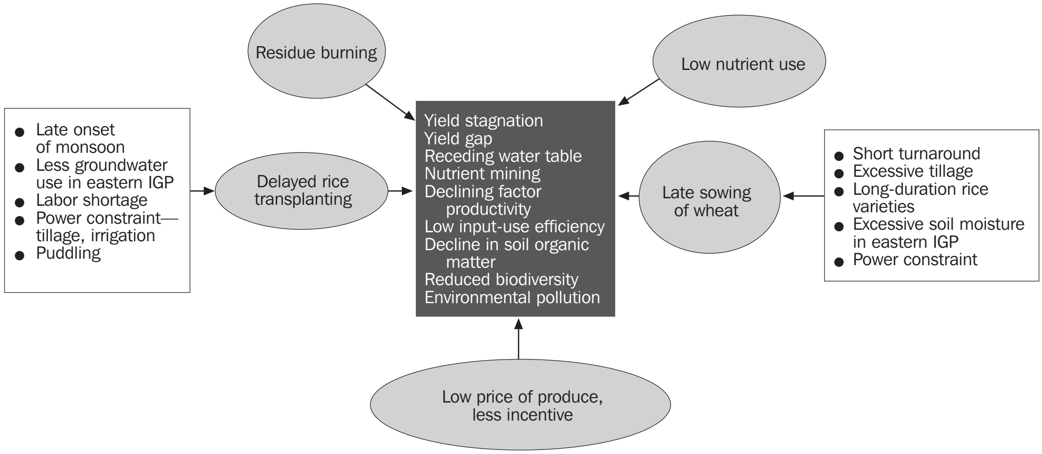

Fig. 6. Sustainability of the rice-wheat system in the Indo-Gangetic Plains.

Table 6. Economic factors of rice and wheat cultivation in India.

Period	Rice			Wheat		
	Minimum support price (Rs. q^{-1})	Cost of production (Rs. ha^{-1})	Cost of cultivation (Rs. q^{-1})	Minimum support price (Rs. q^{-1})	Cost of production (Rs. ha^{-1})	Cost of cultivation (Rs. q^{-1})
1975-76 to 1980-81	7.70	11.12	17.18	3.12	8.56	4.10
1981-82 to 1985-86	5.52	4.80	3.93	4.56	4.49	1.42
1986-87 to 1990-91	9.29	14.24	7.92	6.86	12.87	9.07
1991-92 to 1997-98	9.74	12.46	9.50	11.47	11.50	9.98
1975-76 to 1997-98	8.35	10.02	9.17	6.85	8.16	6.80

some area to grow some alternate high-value crops or switching over to a more profitable enterprise.

Diversification may raise opportunities to raise farm income, generate more employment, and allow a better use of resources. A change in cropping pattern from a rice-wheat monoculture to diversified crops will also lessen biotic and abiotic pressure and help conserve soil and water resources. Diversification into high-value crops will encourage exports of farm produce, bringing more profits. This will, however, require infrastructure development (markets, roads, transport and storage, processing mechanisms), policy changes, and technical innovations. The Indian government's emphasis on the agricultural sector and higher investment in agriculture should result in better infrastructure that will allow rice-wheat farmers to diversify their holdings by including high-value crops. Another dimension of crop substitution/diversification in the rice-wheat system is the inclusion of legumes that may play an important role in improving the sustainability of the production system (Fig. 6). Legumes can play an important role in conserving groundwater and soil nutrients. However, profitability of legumes has remained too low in comparison with rice and wheat (Joshi et al 2000). The prime need is to break the existing yield barriers of legumes and design policies to reduce risk and to improve resource management.

References

Abrol IP, Bronson KF, Duxbury JM, Gupta RK. 2000. Long-term soil fertility experiments in rice-wheat cropping system. RWC Paper Series 6. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India.

Aggarwal PK, Bandyopadhyay SK, Pathak H, Kalra N. 2000. Analysis of yield trends of the rice-wheat system in northwest India. Outlook Agric. 29:259-268.

Aslam M, Mazid A, Hasmi NI, Hobbs PR. 1993. Improving wheat yield in the rice-wheat cropping system of the Punjab through zero tillage. Pakistan J. Agric. Res. 14:8-11.

Balasubramanian V, Hill JE. 2002. Direct seeding of rice in Asia: emerging issues and research needs of the 21st century. In: Pandey S et al, editors. Direct seeding: research strategies and opportunities. Manila (Philippines): International Rice Research Institute. p 15-39.

Balasubramanian V, Morales AC, Cruz RT, Abdulrachman S. 1999. On-farm adoption of knowledge-intensive nitrogen management technologies for the rice system. Nutr. Cycl. Agroecosyst. 53:59-69.

Balasubramanian V, Morales AC, Cruz RT, Thiyagarajan TM, Nagarjun R, Babu M, Abdulrachman S, Hai LH. 2000. Adoption of chlorophyll meter (SPAD) technology for real-time nitrogen management in rice: a review. Int. Rice Res. Notes 25(1):4-8.

Balasubramanian V, Ladha JK, Gupta RK, Naresh RK, Mehla RS, Singh B, Singh Y. 2003. Technology options for rice in the rice-wheat system in South Asia. In: Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication No. 65. Madison, Wis. (USA): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. p 115-148.

Bell MA, Rickman J, Castro Jr EC, Actan LB, McNamara J. 1998. Precision land leveling for rice production in Asia. In: Salokhe VM, Jianxia Z, editors. Proceedings of the International Agricultural Engineering Conference, Asian Institute of Technology (AIT), Bangkok, Thailand, 7-10 Dec. 1998. Bangkok (Thailand): AIT. p 257-264.

Bhuiyan SI. 1992. Water management in relation to crop production: case study in rice. Outlook Agric. 21:293-299.

Brar BS, Singh Y, Dhillon NS, Singh B. 1998. Long-term effects of inorganic fertilizers, organic manures and crop residues on the productivity and sustainability of a rice-wheat cropping system in northwest India. In: Swarup A, Reddy DD, Prasad RN, editors. Long-term soil fertility management through integrated plant nutrient supply. Bhopal (India): Indian Institute of Soil Science. p 169-182.

Cantrell RP, Hettel GP. 2005. Research strategy for rice in the 21st century. In: Toriyama K, Heong KL, Hardy B, editors. Rice is life: scientific perspectives for the 21st century. Proceedings of the World Rice Research Conference held in Tokyo and Tsukuba, Japan, 4-7 November 2004. Los Baños (Philippines): International Rice Reearch Institute, and Tsukuba (Japan): Japan International Research Center for Agricultural Sciences. CD. p 26-37.

Cassman KG, Pingali PL. 1995. Extrapolating trends from long-term experiments to farmers' fields: the case of the irrigated rice system of Asia. In: Barnett V et al, editors. Agricultural sustainability in economic, environmental and statistical terms. London (UK): John Wiley & Sons. p 63-86.

Connor DJ, Timsina J, Humphreys E. 2003. Prospects for permanent beds for the rice-wheat system. In: Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication No. 65. Madison, Wis. (USA): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. p 197-210.

Dawe D, Dobermann A, Moya P, Abdulrachman S, Singh B, Lal P, Li SY, Lin B, Pannaullah G, Sariam O, Singh Y, Swarup A, Tan PS, Zhen Q-X. 2000. How widespread are yield declines in long-term rice experiments in Asia? Field Crops Res. 66:175-193.

De Datta SK. 1986. Technology development and the spread of direct-seeded flooded rice in Southeast Asia. Exp. Agric. 22:417-426.
De Datta SK, Flinn JC. 1986. Technology and economics of weed control in broadcast-seeded flooded tropical rice. In: Noda K, Mercado BL, editors. Weeds and environment in the tropics. Proceedings of the 10th Conference of the Asian Pacific Weed Science Society, Chiang Mai, Thailand.
Dobermann A, Cassman KG, Peng S, Tan PS, Phung CV, Cruz PC Sta, Bajita JB, Adviento MAA, Olk DC. 1996. Precision nutrient management in intensive irrigated rice systems. In: Maximizing sustainable rice yields through improved soil and environmental management. International Symposium, Khon Kaen, Thailand, 11-17 Nov. 1986. Department of Agriculture, Soil and Fertility Society of Thailand, Department of Land Development, and International Society of Soil Science, Bangkok, Thailand. p 133-154.
Dobermann A, Fairshurst T. 2000. Rice: nutrient disorders and nutrient management. Manila (Philippines): International Rice Research Institute. 191 p.
Dobermann A, White PF. 1999. Strategies for nutrient management in irrigated and rainfed lowland rice systems. Nutr. Cycl. Agroceosyst. 53:1-18.
Duxbury JM, Abrol IP, Gupta RK, Bronson KF. 2000. Analysis of long-term soil fertility experiments with rice-wheat rotations in South Asia. In: Abrol IP et al, editors. Long-term soil fertility experiments with rice-wheat rotation in South Asia. Rice-Wheat Consortium Paper Series No. 6. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India. p vii-xxii.
FAO (Food and Agriculture Organization of the United Nations). 1999. FAO production book. Vol. 53. Rome (Italy): FAO.
Flinn JC, De Datta SK. 1984. Trends in irrigated rice yields under intensive cropping at Philippine research stations. Field Crops Res. 9:1-15.
Fujisaka S, Harrington LW, Hobbs PR. 1994. Rice-wheat in South Asia: system and long-term priorities established through diagnostic research. Agric. Syst. 46:69-197.
Guerra RP, Bhuiyan SI, Tuong TP, Barker R. 1998. Producing more rice from less water from irrigated systems. Manila (Philippines): International Rice Research Institute.
Gupta RK, Naresh RK, Hobbs PR, Jiaguo Z, Ladha JK. 2003. Sustainability of post-Green Revolution agriculture: the rice-wheat cropping system of the Indo-Gangetic Plains and China. In: Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication No. 65. Madison, Wis. (USA): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. p 1-26.
Gupta RK, Rickman J. 2002. Design improvements in existing zero-till machines for residue conditions. RWC Travelling Seminar Report Series. 3. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India.
Harrington LW, Fujisaka S, Morris ML, Hobbs PR, Sharma HC, Singh RP, Chodhary MK, Dhiman SD. 1993. Wheat and rice in Karnal and Kurukshetra districts, Haryana, India: farmers' practices, problems and an agenda for action. ICAR, HAU, CIMMYT, Mexico, and IRRI, Los Baños, Philippines.
Hatta S. 1967. Water consumption in paddy field and water-saving rice culture in the tropical zone. Jpn. Trop. Agric. 11:106-112.
Hill JE, Bayer DE, Bocchi S, Ciampett WS. 1991. Direct-seeded rice in temperate climate of Australia, Italy and United States. In: Direct-seeded flooded rice in the tropics. Manila (Philippines): International Rice Research Institute. p 91-102.
Hobbs PR, Giri GS, Grace P. 1997. Reduced and zero tillage options for the establishment of wheat after rice in South Asia. RWC-IGP Paper No. 2. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, and CIMMYT, Mexico, D.F.

Hobbs PR, Gupta RK. 2003. Resource-conserving technologies in the rice-wheat system.In: Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication No. 65. Madison, Wis. (USA): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. p 149-172.

Hobbs PR, Hettel EP, Singh RK, Singh RP, Harrington LW, Singh VP, Pillai KG. 1992. Rice-wheat cropping system in Faizabad district in Uttar Pradesh, India: exploratory surveys of farmers' practices and problems, and needs for further research. ICAR, NDUAT, CIMMYT, Mexico, and IRRI, Los Baños, Philippines.

Hobbs PR, Hettel EP, Singh RP, Singh Y, Harrington LW, Fujisaka S, editors. 1991. Rice-wheat cropping system in Tarai areas of Nainital, Rampur, and Pilibhit districts in Uttar Pradesh, India: sustainability of the rice-wheat system in South Asia: diagnostic surveys of farmers' practices and problems, and needs for further research. CIMMYT, Mexico, ICAR, and IRRI, Los Baños, Philippines.

Hobbs PR, Mehla RS. 2003. The problems of late planting in wheat. In: Addressing resource conservation issues in the rice-wheat system of South Asia: a resource book. Rice-Wheat Consortium for the Indo-Gangetic Plains and International Maize and Wheat Improvement Center, New Delhi, India. p 91-94.

Hobbs PR, Morris ML. 1996. Meeting South Asia's future food requirements from the rice-wheat-cropping system: priority issues facing researchers in the post–Green Revolution era. NRG Paper 96-01. CIMMYT, Mexico, D.F.

Horie T, Nakagawa H, Centeno HGS, Kropff MJ. 1995. The rice crop simulation model SIMRIW and its testing. In: Matthews RB et al, editors. Modeling the impact of climate change on rice production in Asia. CAB International and IRRI, Manila, Philippines. p 51-66.

ICAR (Indian Council of Agricultural Research). 1999. Enhancing the biodegradation of rice residue in rice-based cropping systems to sustain soil health and productivity. Technical Project Representative, Indian Council of Agricultural Research, New Delhi, India.

Janaiah A, Hossain M. 2003. Farm-level sustainability of the intensive rice-wheat system. In: Addressing resource conservation issues in rice-wheat systems of South Asia: a resource book. Rice-Wheat Consortium for the Indo-Gangetic Plains and International Maize and Wheat Improvement Center, New Delhi, India. p 39-45.

Joshi PK. 2003. Nature and speed of agricultural diversification. In: Addressing resource conservation issues in the rice-wheat system of India: a resource book. Rice-Wheat Consortium for the Indo-Gangetic Plains and International Maize and Wheat Improvement Center, New Delhi, India. p 59-62.

Joshi PK, Asokan M, Datta KK, Kumar P. 2000. Socioeconomic constraints to legume production in rice-wheat cropping systems of India. In: Johansen C, Duxbury JM, Virmani SM, Gowda CLL, Pandey S, Joshi PK, editors. Legumes in rice and wheat cropping systems of the Indo-Gangetic Plains: constraints and opportunities. ICRISAT, Patancheru, India. p 176-184.

Kahlown MA, Prathapar SA, Gill MA. 2000. Evaluation of resource conservation technologies in rice-wheat system of Pakistan. OFWM Mimeograph, Lahore, Pakistan.

Kumar K, Goh KM. 2000. Crop residue management: effects on soil quality, soil nitrogen dynamics, crop yield and nitrogen recovery. Adv. Agron. 68:197-319.

Kumar P. 1997. Agricultural productivity and food security in India: implications for policy. Agric. Econ. Res. Rev. 9(2):1-13.

Kumar P. 2003. TFP of crop sector in IGP. In: Rice-wheat information sheet, 46. Rice-Wheat Consortium for the Indo-Gangetic Plains and International Maize and Wheat Improvement Center, New Delhi, India. p 3-4.

Ladha JK, Fischer KS, Hossain M, Hobbs PR, Hardy B, editors. 2000. Improving the productivity and sustainability of rice-wheat systems of the Indo-Gangetic Plains: a synthesis of NARS-IRRI research partnership. IRRI Discussion Paper Series No. 40. Los Baños (Philippines): International Rice Research Institute. 31 p.

Ladha JK, Pathak H, Padre AT, Dawe D, Gupta RK. 2003. Productivity trends in intensive rice-wheat cropping systems in Asia. In: Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication No. 65. Madison, Wis. (USA): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. p 45-76.

Lal P. 1985. Rice research at Pantnagar. Exp. Sta. Tech. Bull. 112. G.B. Pant University of Agriculture and Technology, Pantnagar, India. p 30-32.

Malik RK. 1996. Herbicide resistant weed problems in developing world and methods to overcome them. In: Proceedings of the 2nd International Weed Science Congress, Copenhagen, Denmark. FAO, Rome. p 665-673.

Malik RK, Yadav A, Singh S, Malik RS, Balyan RS, Banga RS, Sardana PK, Jaipal S, Hobbs PR, Gill G, Singh S, Gupta RK, Bellinder R. 2002. Herbicide resistance management and evaluation of zero-tillage: a success story. Research Bulletin, Haryana Agricultural University, Hissar, India.

Mary B, Recous S, Darwis D, Robin D. 1996. Interaction between decomposition of plant residues and nitrogen cycling in soil. Plant Soil 181:71-82.

Misra RD. 2003. Wheat research at Pantnagar. Research Bulletin No. 132. G.B. Pant University of Agriculture and Technology, Pantnagar, India. p 26-27.

Nayyar VK. 2003. Soil micronutrient deficiencies in the rice-wheat cropping system. In: Addressing resource conservation issues in rice-wheat systems of South Asia: a resource book. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India. p 157-162.

Ortiz-Monasterio JE, Dillon SS, Fischer RA. 1994. Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. Field Crops Res. 37:169-184.

Padre AT, Ladha JK. 2004. Integrating yield trends of rice-wheat systems using the linear mixed effect model and meta analysis. In: Rice-wheat information sheet, 48. Rice-Wheat Consortium for the Indo-Gangetic Plains and International Maize and Wheat Improvement Center, New Delhi, India. p 1-3.

Pandey S, Velasco L. 2005. Trends in crop establishment methods in Asia and research issues. In: Rice is life: scientific perspectives for the 21st century. Proceedings of the World Rice Research Conference held in Tokyo and Tsukuba, Japan, 4-7 November 2004. Los Baños (Philippines): International Rice Research Institute, and Tsukuba (Japan): Japan International Research Center for Agricultural Sciences. CD. p 178-181.

Paroda RS, Woodhead T, Singh RB. 1994. Sustainability of the rice-wheat production system in Asia. RAPA Pub. 1994/11. FAO, Bangkok, Thailand.

Pathak H, Biswas DR, Singh R. 2002. Fertilizer use and environmental quality. Fert. News 47(11):13-20.

Peng S, Garcia FV, Laza RC, Sanico AL, Visperas RM, Cassmann KG. 1996. Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crops Res. 47:243-252.

Penning de Vries FWT. 1993. Rice production and climatic change. In: Penning de Vries FWT et al, editors. Systems approaches for agricultural development. Dordrecht (Netherlands): Kluwer Academic Publishers. p 175-179.

Ponnamperuma FN. 1979. Soil problems in the IRRI farm. IRRI Thursday Seminar, 8 Nov. 1979, IRRI, Los Baños, Philippines.

Prihar SS, Grewal SS. 1985. Improving irrigation water use efficiency in rice-wheat cropping sequence: technical and policy issues. In: National seminar on water management: the key to developing agriculture. New Delhi (India): Agricode Publishing Academy.

Randhawa AS, Dhillon SS, Singh D. 1981. Productivity of wheat varieties as influenced by the time of sowing. J. Res. Punjab Agric. Univ. 18:227-233.

Rickman J, Bunna S, Sinath P. 1998. Agricultural engineering. In: Program report for 1998. Los Baños (Philippines): International Rice Research Institute. p 142.

Sakthivadival R, Chawala AS. 2003. Innovation in ground water recharge. In: Addressing resource conservation issues in the rice-wheat systems of South Asia: a resource book. Rice-Wheat Consortium for the Indo-Gangetic Plains and International Maize and Wheat Improvement Center, New Delhi, India. p 180-186.

Samra JS, Singh B, Kumar K. 2003. Managing crop residues in the rice-wheat system of Indo-Gangetic Plains. In: Improving the productivity and sustainability of rice-wheat systems: issues and impact. ASA Special Publication No. 65. Madison, Wis. (USA): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. p 173-196.

Sandhu BS, Khera KI, Prihar SS, Singh B. 1980. Irrigation need and yield of rice on a sandy loam soil as affected by continuous and intermittent submergence. Indian J. Agric. Sci. 50:492-496.

Sarkar A, Yadav RL, Gangwar B, Bhatia PC. 1999. Crop residues in India. Technical Bulletin. Project Directorate of Cropping System Research, Modipuram, India. 34 p.

Saunders D.A. 1990. Crop management research summary of results. Monograph 5. Wheat Research Center, Nashipur, Bangladesh.

Sayre KD. 2000. Effects of tillage, crop residue retention and nitrogen management on the performance of bed-planted, furrow-irrigated spring wheat in northwest Mexico. In: Proceedings of the 15th Conference of the International Soil Tillage Research Organization, Fort Worth, Tx., 2-7 July 2000. CD.

Sharma PK. 1998. Effect of crop residue management practices and green manuring on nutrient dynamics and soil productivity in rice-wheat cropping system. Ph.D. thesis. G.B. Pant University of Agriculture and Technology, Pantnagar, India.

Singh Y. 1995. Rice-wheat cropping system. NARP basic research project, progress report 1994-95. G.B. Pant University of Agriculture and Technology, Pantnagar, India.

Singh Y, Singh G, Johnson DE, Mortimer M. 2005. Changing from transplanted rice to direct seeding in rice-wheat cropping systems in India. In: Rice is life: scientific perspectives for the 21st century. Proceedings of the World Rice Research Conference held in Tokyo and Tsukuba, Japan, 4-7 November 2004. Los Baños (Philippines): International Rice Research Institute, and Tsukuba (Japan): Japan International Research Center for Agricultural Sciences. CD. p 198-201.

Singh G, Chandra H. 2002. Production and economic factors in growth of Indian agriculture. Bhopal (India): Central Institute of Agricultural Engineering.

Singh U, Godwin DC, Ritchie JT, Bowen WT, Wilkens PW, Baer B, Hoogenboom G, Hunt LA. 1998. CERES-RICE V3.5. International Fertilizer Development Center, Michigan State University, University of Georgia, USA.

Swaminathan MS. 2003. For a season of plenty. The Week, 28 Dec. 2003.

Thakur TC. 2003. Crop residues as animal feed. In: Addressing resource conservation issues in rice-wheat systems of South Asia: a resource book. Rice-Wheat Consortium for the Indo-Gangetic Plains and International Maize and Wheat Improvement Center, New Delhi, India. p 256-258.

Timsina J, Connor D. 2001. The productivity and sustainability of rice-wheat cropping systems: issues and challenges. Field Crops Res. 69:93-132.

Tiwari KN. 2002. Balanced fertilization for food security. Fert. News 47(11):113-122.

Tullberg JN, Ziebarth PJ, Li Y. 2001. Tillage and traffic effects on runoff. Aust. J. Soil Res. 39:249-257.

Turner FT, Jund MF. 1994. Assessing the nitrogen requirement of rice crops with chlorophyll meter method. Aust. J. Ext. Afric. 34:1001-1005.

Verma UN, Srivastava VC. 1989. Weed management in wheat under zero and optimum tillage conditions. Indian J. Agron. 34:176-179.

Verma UN, Srivastava VC. 1994. Production technology of non-tilled wheat after puddled transplanted rice. Indian J. Agric. Sci. 64:277-284.

Woodhead TR, Huke R, Huke E, Balababa L. 1994. Rice-wheat atlas of India. An IRRI, CIMMYT, and ICAR Publication. Manila (Philippines): International Rice Research Institute.

Yadav RL, Prasad K, Gangwar KS. 1998. Analysis of ecoregional production constraints in rice-wheat cropping system. PDCSR Bull. 98-2. Project Directorate on Cropping Systems Research, Modipuram, India.

Yoshida S, Parao FT. 1976. Climatic influences on yield components of lowland rice in the tropics. In: Climate and rice. Manila (Philippines): International Rice Research Institute. p 471-494.

Notes

Author's address: Vice-Chancellor, G.B. Pant University of Agriculture and Technology, Pantnagar, India.

Issues related to direct seeding of rice in rainfed cropping systems in northwest Bangladesh

A.M. Mortimer, C.R. Riches, M. Mazid, S. Pandey, and D.E. Johnson

Economic factors and developments in rice production technologies are the major drivers that have led to the adoption of direct seeding of rice in place of transplanting in Asia. The primary economic motives for a shift to direct seeding are the savings in labor cost and the possibility of crop intensification. A key development challenge in the drought-prone rainfed agriculture of the Barind Tract of northwest Bangladesh is to simultaneously improve the reliability and yield of monsoon rice while improving total system productivity by increasing the area planted to drought-tolerant postrice crops. Research trials and field-scale evaluation by farmers have demonstrated that dry direct seeding or wet seeding of pregerminated rice seed reduces labor for crop establishment, results in rice yields similar to or higher than those from conventional transplanting, and advances harvest by 7–10 days. Earlier harvest has the potential to reduce the risk of terminal drought in rice when the monsoon ends abruptly and increases the opportunity for establishing a postrice crop of chickpea on residual moisture. Herbicide use is essential with direct seeding and this further reduces rice production costs. This modified rice/legume system using direct seeding is knowledge-intensive. Widespread sustained adoption will depend on farmers undertaking timely tillage, adequate land leveling, and timely application of herbicides. Extension/farmer training supported by clear decision support frameworks will be needed to provide farmers with access to the knowledge needed to implement direct seeding effectively.

Economic factors and developments in rice production technologies have been the major drivers leading to the adoption of direct-seeding methods for rice establishment in place of transplanting in Asia (Pandey and Velasco 2002). The rising cost of agricultural labor, the need to intensify rice production through double and/or triple cropping, the development of high-yielding short-duration modern varieties, and the availability of chemical weed control methods largely promoted this change, as evidenced in Malaysia and Thailand in the late 1980s and 1990s. In the 21st century, along with population pressure, the rising scarcity of agricultural land and water and continuing shortages of labor will maintain pressure for a shift toward direct-seeding methods. In low-income Asian countries with per annum population growth rates of 1–1.5% (such as Bangladesh, India, Indonesia, Myanmar, the Philippines, and Vietnam), the anticipated growth in rice demand of 30–50% over the next 30 years will accentuate the potential role of direct seeding of rice.

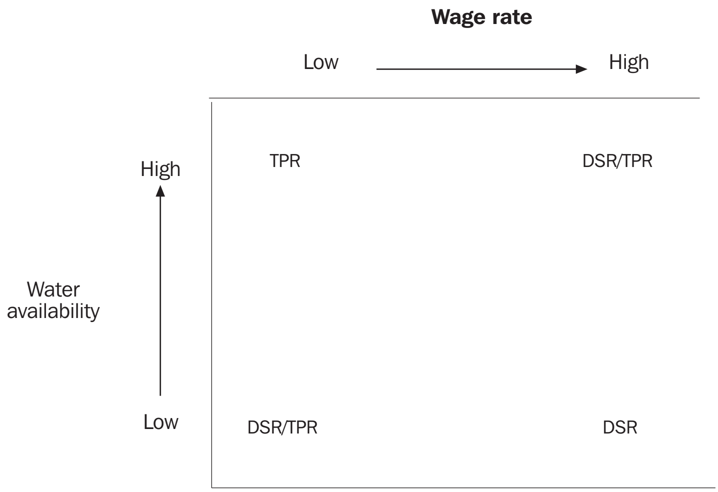

Fig. 1. Wage rate and water availability as determinants of crop establishment methods (from Pandey and Velasco 2002). DSR = direct-seeded rice, TPR = transplanted rice.

Drivers of change in rice establishment methods in Asia

In overview, the availability of water and the opportunity cost of labor can be considered to be the major determinants of rice crop establishment methods (Fig. 1). A low wage rate and assured supply of adequate water are favorable for transplanting. Incentives for direct seeding increase when water availability is low (or uncertain) and wage rates are high. Much of the recent spread of direct seeding in Southeast Asian countries has been in response to rising wage rates. When water availability is low (or uncertain) and the wage rate is low, either dry direct seeding or transplanting can be used to establish rice, depending on field hydrological conditions.

The response to rising labor costs has been either a retention of transplanting but with a switch to mechanical transplanting (e.g., Japan, Korea, and Taiwan) or a shift to direct seeding (e.g., Malaysia and Thailand). Small farm size, intensive cultivation of rice, a long history of transplanting culture, and the relatively high price of rice in some Asian countries may partially explain the adherence to transplanting.

From farm studies, Pandey and Velasco (1999) have shown that direct-seeding methods produce higher income relative to transplanting, despite a slightly lower average yield than that of transplanted rice. A higher net profit arises since savings in labor costs outweigh the value of loss in output. This has occurred especially in areas where the cost of labor has risen rapidly in relation to the price of rice. In addition, total farm income has increased where direct seeding has facilitated double cropping of rice in areas that previously had only one crop of transplanted rice.

Given that the primary economic motives for a shift to direct seeding are the savings in labor cost and the possibility of crop intensification, prioritizing research issues depends on which motive is likely to play a dominant role. If the driving force for transition to direct seeding is the rapidly rising wage rate, research and development to implement the adoption of labor-saving technological innovations (mechanical tillage and labor-saving weed control methods) will assume a high priority. Where drought and early submergence are agroecological constraints, both rice varietal improvement and modifications to crop and natural resource management practices may be needed.

Contrastingly, if crop intensification is the major reason for direct seeding, research to facilitate early crop establishment (and the consequent earlier crop harvesting) will carry a higher priority, as this will permit timely planting of a subsequent crop. The development of short-duration varieties is clearly important. Even though agricultural labor costs may be low, intensification of land use may lead to labor shortages because of peak labor demand during the harvesting of the previous crop and establishment of the succeeding crop within a short period. In such instances, mechanization in land preparation may be essential to reduce the turnaround time between crops and ensure a more stable yield of the second crop.

A major threat to yields of direct-seeded rice crops is weed competition and high costs of weed control (or unavailability of efficient weed control procedures), which will be a major factor constraining the widespread adoption of direct seeding. Empirical analyses have indicated that the technical efficiency of rice production is lower and more variable for direct-seeded rice than for transplanted rice (Pandey and Velasco 1999). This suggests the existence of a higher "yield gap" between the "best practice" and the average farmers' practices when rice is direct-seeded. This variability may be partly due to the use of varieties that were originally developed for transplanted culture and cultivars that are specifically targeted for direct seeding (both wet and dry) may need to be developed.

Precise water management is also a critical factor for high productivity for both dry- and wet-seeded rice (De Datta and Nantasomsaran 1991). In dry seeding, maintenance of an aerobic soil early in crop life to ensure establishment and high seedling vigor is essential. Likewise, water management in wet-seeded rice needs to be precise to achieve seedling establishment and then controlled flooding/drainage may be required for herbicide application and crop growth and management. A high level of control of water flow on irrigated fields is hence desirable and predicates land leveling. Suitable modifications of irrigation infrastructure may not only ensure a high yield of direct-seeded rice but also improve water-use efficiency. In rainfed environments, the rainfall patterns and land position in relation to natural drainage will determine the opportunities for direct-seeding options. Recent research conducted in rainfed rice systems of Bangladesh to explore the potential for direct seeding is described below.

Case study: rainfed cropping systems in northwest Bangladesh

The High Barind Tract of northwest Bangladesh is drought-prone, with the majority of the 1,200–1,400 mm mean annual rainfall falling in June to October. Limited irrigation potential restricts cropping intensity to 175%, considerably less than in districts where irrigation allows two or three rice crops each year (Nur-E-Alahi et al 1999). The majority of farmers produce a single crop of transplanted rainfed rice, grown in this monsoon season. Some 80% of the area then lies fallow in the *rabi* season that follows the rice harvest. The challenge and opportunity in the Barind is to simultaneously improve the reliability and yield of rice while increasing total system productivity by increasing the area planted to rabi-season crops such as chickpea, linseed, and mustard (Mazid et al 2003).

Mazid et al (2002, 2003) have proposed that farm productivity in the Barind can be increased by switching from transplanting to direct seeding of rice (DSR) to allow more reliable establishment of rabi crops on residual moisture immediately after the rice harvest. Chickpea, a drought-tolerant and high-value crop, can be grown successfully when seeded after the rice harvest in late October to mid-November. This can make significant contributions to higher productivity and improved farm income. Late onset of the monsoon delays transplanting as a minimum of 600 mm of cumulative rainfall is needed to complete plowing, puddling, and transplanting. Direct seeding, however, can be completed after plowing following only 150 mm of cumulative rainfall (Saleh and Bhuiyan 1995). Earlier planted DSR rice matures 1–2 weeks before transplanted rice, thus reducing the risk of terminal drought and allowing earlier planting of a following nonrice crop (Saleh et al 2000). An earlier rice harvest can also be achieved by planting early-maturing rice varieties. Swarna, the most widely grown rice cultivar, matures after 140–145 days and when transplanted may not be harvested until early to mid-November. In many years, soil is drying rapidly at this time, reducing the likelihood of successful chickpea establishment.

DSR reduces labor and draft power requirements for rice establishment by 16% and 30%, respectively, compared with TPR. However, weeds are a major constraint to the adoption of DSR as the inherent advantage of weed control afforded by transplanted rice in standing water is lost. Labor shortages for many households prevent timely first weeding of transplanted rice so that with current practices 34% of farmers lose over 0.5 t ha^{-1} of the attainable rice yield because of weed competition (Mazid et al 2001). The additional weed problems in DSR, however, can be overcome by applying a preemergence herbicide.

As discussed above, improvement of total farm productivity requires the successful integration of several component technologies and an interlinked research agenda. Research and current understanding on the productivity of direct-seeded, early-maturing rice cultivars with herbicide application, followed by chickpea in the postrice season, are reported below.

Methods

On-station and on-farm experiments were conducted in the region of Rajabari, Rajshahi, Bangladesh. A long-term on-station (systems) trial compared crop establishment methods, fertilizer regimes, and weed control methods for two cultivars. On-farm trials examined cultivar performance and chickpea yields.

Systems trial

The productivity of two rice cultivars when direct-seeded or transplanted was evaluated in the Barind from 2001 to 2003 under differing nutrient regimes. The modern cultivar BRRIdhan 39 (maturity 120–125 d) was compared with the widely grown Swarna (maturity 145–150 d). The experiment was conducted with a split-split plot design with main plots (3) as crop establishment and associated weed management, subplots (4) as nutrient management, and sub-subplots (2) as cultivars. Establishment treatments were (1) *transplanted rice (TPR)*—soil puddled prior to transplanting and plots hand-weeded twice at 30 and 45 d after transplanting (DAT); (2) *direct-seeded rice (DSR)*—soil plowed prior to dry seeding (2001) or plowed and puddled before direct seeding of pregerminated seed (2002 and 2003) in rows by hand, with hand weeding at 21, 33, and 45 d after sowing (DAS); (3) *direct-seeded rice with chemical weed control (DSRH)*—as for DSR but with oxadiazon (375 g a.i. ha^{-1}) applied 2–4 d after seeding with one hand weeding at 33 DAS. Nutrient regimes were (kg ha^{-1}) (1) single superphosphate, 40 P + 40 K; (2) compound 60 N + 40 P + 40 K; (3) farmyard manure (FYM) + inorganic fertilizer totaling 60 N + 50 P + 50 K; and (4) diammonium phosphate (18% N) + Guti (slow-release urea, 45% N) totaling 43 N + 40 P + 40 K. Rice was harvested in 5-m^2 areas. Biomass of individual weed species was recorded in two unweeded quadrats per plot at 28 DAS/DAT and total weed biomass at 45 DAS/DAT.

On-farm verification of the DSR-rabi system

Trials were undertaken at 16 sites during the 2003 monsoon season to verify the profitability of a DSR-chickpea system. Chickpea (cv. Barisola 2) was sown after the harvest of Swarna or

Table 1. Effect of rice establishment method and rice cultivar on grain yield of rice and a postrice chickpea crop (t ha^{-1} ± S.E.), 2002-04, Rajabari, northwest Bangladesh.

Crop	Transplanted rice		Direct-seeded rice	
	BR39	Swarna	BR39	Swarna
Rice				
2001	1.92 ± 0.10	2.79 ± 0.19	2.91 ± 0.12	2.85 ± 0.11
2002	2.80 ± 0.13	2.59 ± 0.11	2.96 ± 0.08	3.75 ± 0.15
2003	0.61 ± 0.08	0.51 ± 0.05	1.62 ± 0.21	2.67 ± 0.16
Chickpea				
2001-02	–[a]	–	1.01 ± 0.06	0.91 ± 0.05
2002-03	–	–	0.76 ± 0.05	0.49 ± 0.04
2003-04	–	–	0.38 ± 0.04	0.16 ± 0.02

[a]– = chickpea not sown.

three shorter-duration BRRIdhan cultivars established by either transplanting or direct seeding. Before dry direct seeding in June, the land was plowed (at least 3 times) with an animal-drawn country plow and leveled with a ladder. Seed was sown in lines by hand into furrows opened by a hand-pulled *lithao*. Seedbeds were established at the same time and seedlings were transplanted at approximately 30 d after sowing following conventional plowing and puddling operations. In direct-seeded rice, a single application of oxadiazon (375 g a.i. ha^{-1}) was made to control weeds, whereas, in transplanted rice, pretilachlor (450 g a.i. ha^{-1}) was applied.

Seasonal variation in rainfall was considerable. The annual rainfall in 2001, 2002, and 2003 was 1,475, 1,464, and 932 mm, respectively. In July 2003, rainfall was 2.5 times less than in the same month in previous years and in 2001 was highest in October.

Results

Systems trial

There were significant effects of cropping system on phenology of rice. Flowering was always later with cv. Swarna and under transplanting (P <0.05). On average, grain-fill duration was similar over varieties, but was reduced by transplanting, especially for BR39. Direct-seeded rice reached maturity significantly earlier than transplanted rice (P <0.01), allowing chickpea to be planted 8–16 d earlier. Swarna significantly outyielded BR39 in 2002 when direct-seeded, and also under transplanting in 2001 (P <0.05) (Table 1). However, no significant difference was observed between varieties under transplanting in 2002 and under direct seeding in 2001. Late transplanting because of drought from early July to mid-August severely depressed yields of transplanted rice in 2003, whereas, under direct seeding, yields were higher and Swarna gave 1 t ha^{-1} higher yield than BR39.

Nutrient application (NPK compound or DAP + Guti) increased tiller and panicle number, plant height, and grain yield in both cultivars. In transplanted rice, BR39 had fewer panicles than Swarna. The main weed species present at the site were *Fimbristylis miliacea*, *Cyperus iria, C. halpan,* and *Cynodon dactylon.* In the first two seasons, greater weed biomass developed in rice established by direct seeding than under transplanting (P <0.05).

Overall, more weed biomass was present where DAP + Guti was used. When herbicide was used for weed control in direct-seeded plots, weed biomass was least under all fertilizer treatments

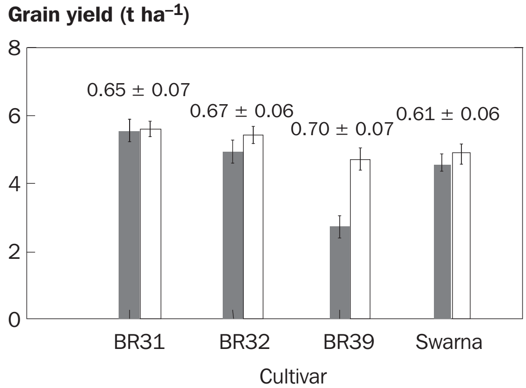

Fig. 2. Productivity (t ha^{-1}) of rice and chickpea grown in transplanted rice (open columns) and direct-seeded rice (solid columns) systems. Data are means of 16 on-farm sites in 2003 (monsoon and rabi seasons). Weed control in rice by preemergence herbicide. Data above each pair of columns are chickpea yields (t ha^{-1} ± S.E.).

except DAP + Guti. In transplanted plots and direct-seeded plots not treated with oxadiazon, the rank order of weed biomass at 45 DAT was sedge > grass > broadleaf weeds. The use of oxadiazon changed the ranking: grass > sedge > broadleaf weeds.

The yields of chickpea after direct-seeded rice were significantly higher following BR39 than after Swarna in 2002 and 2003 (P <0.001) and were elevated in 2001 (Table 1).

On-farm verification of the DSR-rabi system

Rice yields were considerably higher on-farm in 2003 (Fig. 2) as the drought in July and August was more prolonged at the site of the systems trial. On-farm, the yields of Swarna, BR31, and BR32 were independent of crop establishment method, whereas yields of transplanted BR39 were over 1.8 t ha^{-1} higher than when direct-seeded. Chickpea yields were not significantly affected by the preceding rice cultivar.

Discussion

The systems trial confirmed that replacing transplanted rice with direct-seeded rice could improve farm productivity in the Barind by allowing greater opportunity to grow a high-value rabi crop. The early-season weed flush associated with direct seeding can be successfully controlled by oxadiazon applied preemergence. However, one subsequent manual weeding will be essential for yield protection from weed competition and to prevent the buildup of *Alternanthera sessilis*, *Cyperus iria*, and *Paspalum distichum* in particular. While extensive rice cultivar evaluation is under way, BR31 and BR32 represent promising lines for direct seeding. BR39, on the other hand, is not suitable for direct seeding as sterility appears to be a major problem when it is planted early as it then tends to flower in the rains. Successful chickpea cropping after rice is contingent upon the presence of residual soil moisture after rice harvest and the time-window for successful chickpea establishment may be difficult to exploit. Chickpea yields in the systems trial reported above were always higher because crops were established immediately after the rice harvest. In on-farm trials in 2003, the potential advantage from direct seeding was not evident because widespread rain showers during the first two weeks of October favored establishment regardless of the time of the rice harvest. High chickpea yields were not achieved, however, because of late-season drought.

Our associated socioeconomic studies indicate that, although farmers are keen to gain additional income from growing chickpea, many, particularly resource-poor sharecroppers who pass 50% of their production to the landlord, need practices that maximize rice yield. To be widely adopted for direct seeding in place of Swarna, an early-maturing rice cultivar will need to be high-yielding and sheath-blight-resistant. The reduction in input costs (no nursery and substitution of labor with a herbicide) associated with direct seeding and early planting of chickpea was evaluated favorably by on-farm trial farmers in 2003. They considered that even the relatively low chickpea yields obtained on-farm in 2003, after either transplanted or direct-seeded rice, provided worthwhile additional income given chickpea's low input costs and high market value. Further studies are continuing to evaluate the profitability and sustainability of direct-seeding and rice-chickpea systems under farmer management.

Concluding remarks

The case study described above exemplifies the interrelated biophysical research topics that must be examined in developing technologies to improve farmer livelihoods in systems in which direct-seeded rice is a key component. The technologies (rice and chickpea seeding, herbicide application, water management) are individually knowledge-intensive and place a premium on the timeliness of agricultural operations. This is turn requires availability of resources (machinery, labor, seed, herbicide), advanced planning, and a cropping systems perspective. Promoting the adoption of these technologies in Bangladesh has only begun recently and small-farmer field groups working in close association with researchers and extension have proved successful.

References

De Datta SK, Nantasomsaran P. 1991. Status and prospects of direct seeded flooded rice in tropical Asia. In: Direct seeded flooded rice in the tropics: selected papers from the International Rice Research Conference, Manila, Philippines. Manila (Philippines): International Rice Research Institute. p 1-16.

Mazid MA, Jabber MA, Mortimer M, Wade LJ, Riches CR, Orr AW. 2003. Improving rice-based cropping systems in north-west Bangladesh: diversification and weed management. The BCPC International Congress on Crop Production and Protection. p 1029-1034.

Mazid MA, Jabber MA, Riches CR, Robinson EJZ, Mortimer M, Wade LJ. 2001. Weed management implications of introducing dry-seeded rice in the Barind Tract of Bangladesh. Proceedings of the BCPC Conference, Weeds 2001. 1:211-216.

Mazid MA, Bhuiyan SI, Mannan MA, Wade LJ. 2002. Dry-seeded rice for enhanced productivity of rainfed drought-prone lands: lessons from Bangladesh and the Philippines. In: Pandey S, Mortimer M, Wade LJ, Tuong TP, Hardy B, editors. Direct seeding in Asian rice systems: strategic research issues and opportunities. Manila (Philippines): International Rice Research Institute. p 185-201.

Nur-E-Elahi AH, Khan MR, Siddique A, Saha M, Nasim M, Shahidullah SM. 1999. Existing cropping patterns of Bangladesh: potential techniques and strategies for improving systems productivity. In: Mandal MR, editor. Proceedings of the workshop on modern rice cultivation in Bangladesh. Gazipur (Bangladesh): Bangladesh Rice Research Institute. p 107-169.

Pandey S, Velasco LE. 1999. Economics of alternative rice establishment methods in Asia: a strategic analysis. Social Sciences Division Discussion Paper. Manila (Philippines): International Rice Research Institute.

Pandey S, Velasco LE. 2002. Economics of direct seeding in Asia: patterns of adoption and research priorities. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B, editors. Direct seeding: research issues and opportunities. Manila (Philippines): International Rice Research Institute. p 3-14.

Saleh AFM, Bhuiyan SI. 1995. Crop and rainwater management strategies for increasing productivity of rainfed lowland rice systems. Agric. Syst. 49:259-276.

Saleh AFM, Mazid MA, Bhuiyan SI. 2000. Agrohydrologic and drought risk analyses of rainfed cultivation in northwest Bangladesh. In: Tuong TP, Kam SP, Wade LJ, Pandey S, Bouman BAM, Hardy B, editors. Characterizing and understanding rainfed environments. Manila (Philippines): International Rice Research Institute. p 233-244.

Notes

Authors' addresses: A.M. Mortimer, School of Biological Sciences, University of Liverpool, L69 3ZD UK; C.R. Riches, Natural Resources Institute, University of Greenwich, ME4 4TB, UK; M. Mazid, Bangladesh Rice Research Institute (BRRI) Post Rangpur, Cadet College, Rangpur, Bangladesh; S. Pandey and D.E. Johnson, International Rice Research Institute, Los Baños, Philippines.

Acknowledgments: Work in Bangladesh was partially funded by the UK Department for International Development (Crop Protection Programme Project R8234). However, the views expressed are not necessarily those of DFID. Support has also been received from the Consortium for Unfavorable Rice Environments (ADB/IRRI).