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

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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.

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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-

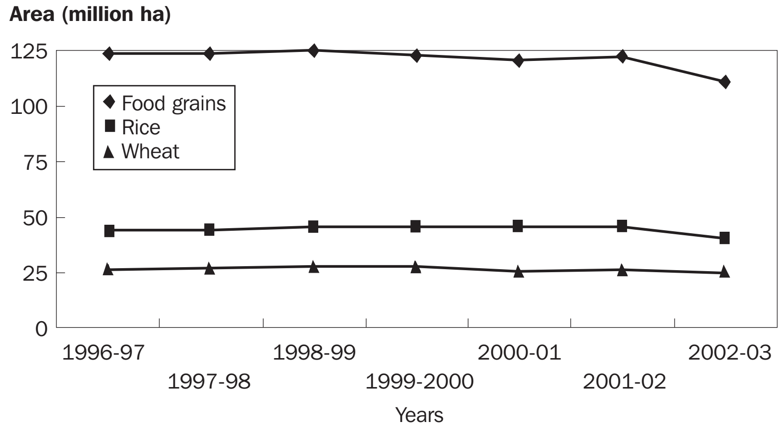

Fig. 1. Area under rice, wheat, and total food grains in India.

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).

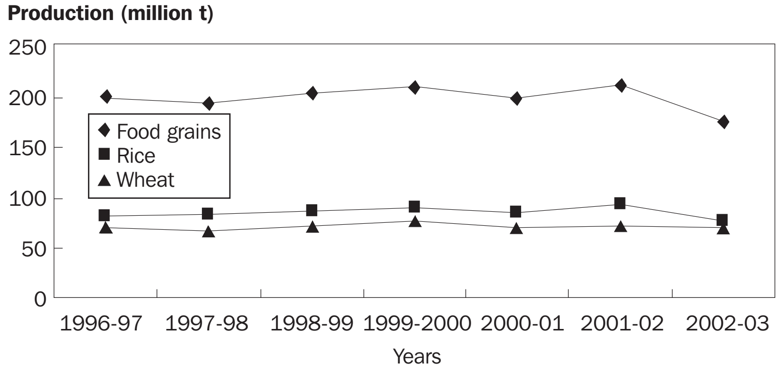

Fig. 2. Production of rice, wheat, and total food grains in India.

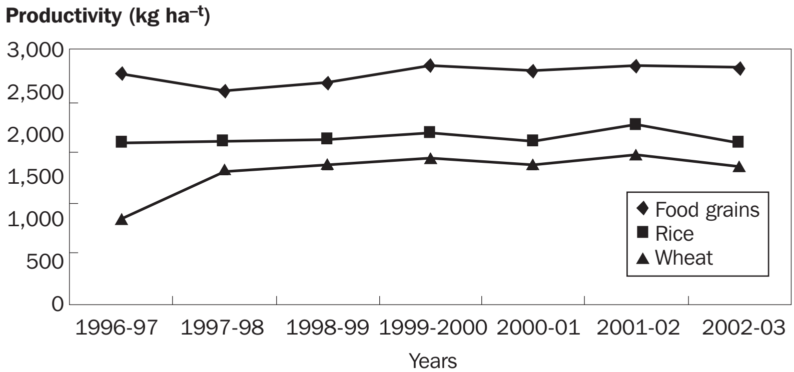

Fig. 3. Productivity of rice, wheat, and total food grains in India.

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.

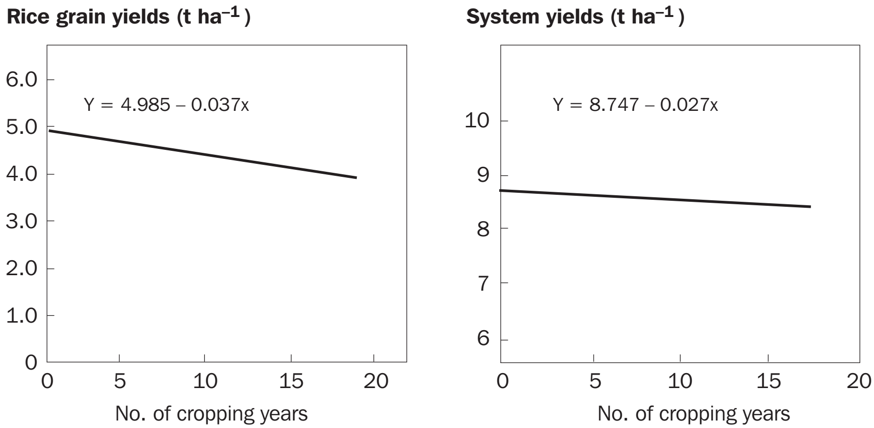

Fig. 4. Aggregate yield trends in rice and system yield (rice + wheat) in long-term experiments in the rice-wheat cropping system in the Indo-Gangetic Plains.

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).

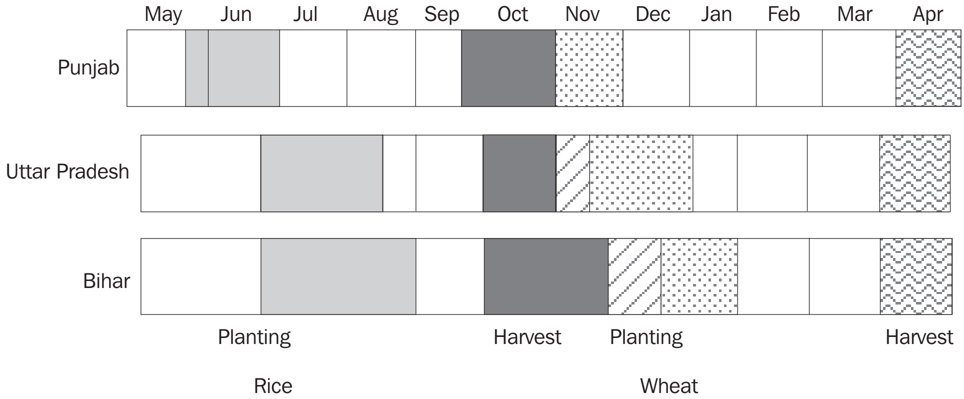

Fig. 5. The rice-wheat calendar in Punjab, Uttar Pradesh, and Bihar.

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

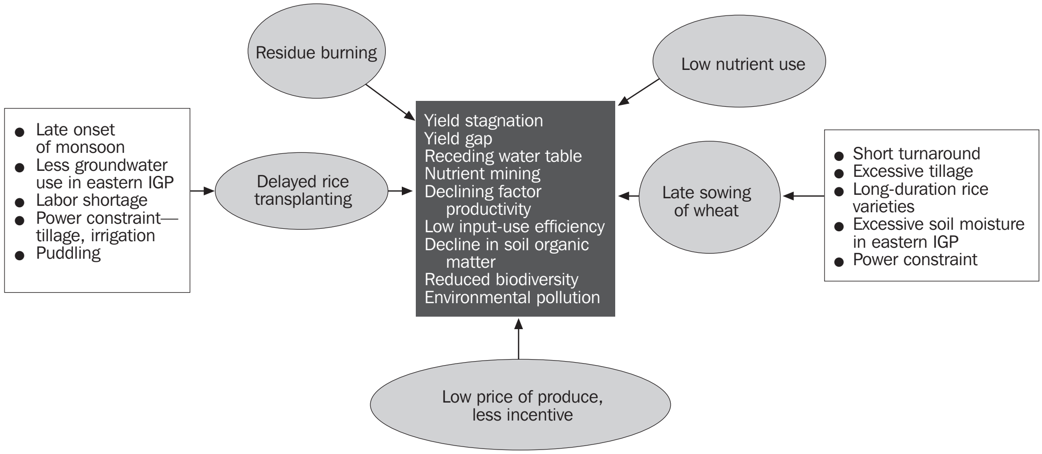

Fig. 6. Sustainability of the rice-wheat system in the Indo-Gangetic Plains.

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.

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

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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.

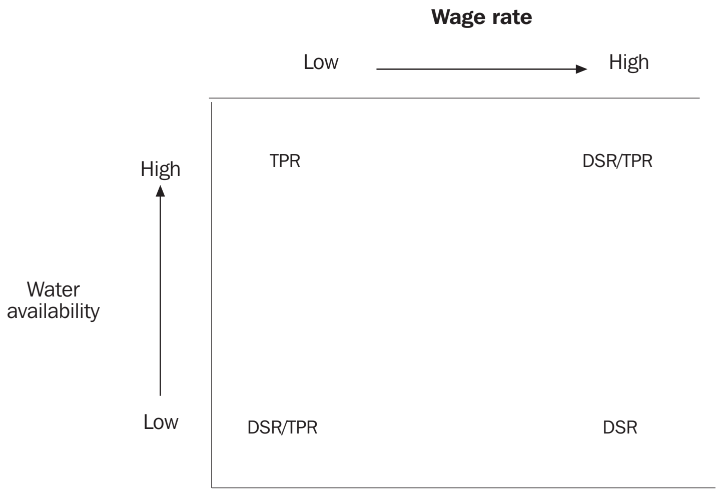

Fig. 1. Wage rate and water availability as determinants of crop establishment methods (from Pandey and Velasco 2002). DSR = direct-seeded rice, TPR = transplanted rice.

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

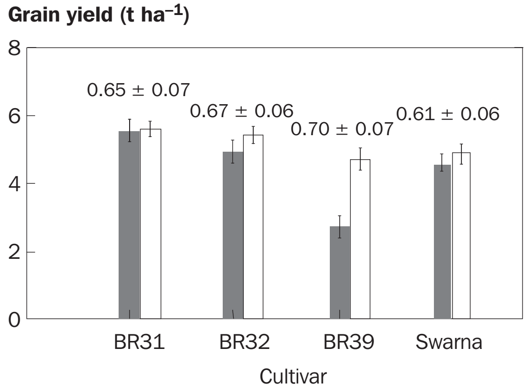

Fig. 2. Productivity (t ha^{-1}) of rice and chickpea grown in transplanted rice (open columns) and direct-seeded rice (solid columns) systems. Data are means of 16 on-farm sites in 2003 (monsoon and rabi seasons). Weed control in rice by preemergence herbicide. Data above each pair of columns are chickpea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

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Characterization

Cropping systems and weed flora of rice and wheat in the Indo-Gangetic Plains

Y. Singh and Govindra Singh

The Indo-Gangetic Plains (IGP), spread over parts of Pakistan, northern India, southern Nepal, and Bangladesh, though uniform in soil type, mostly Inceptisols, vary considerably in climate, physiography, and social conditions and also in cropping systems. The western semiarid, dry, and hot region is dominated by the rice-wheat cropping system; 85% of the cropped area in Punjab is under these two crops. Toward the east, ecosystems are more diverse and crop diversification increases. The entire IGP can be divided into five transects where cropping systems vary. Transect 1 covers parts of Pakistan, where, in Punjab Province, long-duration Basmati-type rice is grown predominantly, thus delaying wheat sowing. In Sindh Province, because of poor drainage, wheat sowing is late and hence wheat yields are low. Transect 2 covers Punjab and Haryana states, where infrastructure is well developed. The entire area is irrigated and yields are high. However, groundwater resources are under severe pressure and the water table is declining. Transect 3 covers mainly western and central Uttar Pradesh and Tarai areas. Here, after rice-wheat, sugarcane becomes an important crop and cropping systems are more diversified. Transect 4 covers eastern Uttar Pradesh and Bihar, where flood and waterlogging are major constraints. Irrigation is mostly in the winter season and cropping systems are mainly rice based. Input use is low and so yields are low. Underground water is underused and a large area remains fallow during the winter season. In Transect 5, covering West Bengal and Bangladesh, where wheat is not an important crop, two to three crops of rice are grown in a year. Jute is an important crop and sizable area is under vegetables. The weed species in different transects are quite common. Among the grasses, *Echinochloa* species dominate. *Caesulia axillaris* and *Ludwigia* species are important broadleaf weeds, whereas, among sedges, *Cyperus* species and *Fimbristylis miliacea* are important. Intensity of weeds varies considerably from west to east: *Echinochloa* species dominate in the west and *Ludwigia* species in the east. A case study in western IGP recorded weed density and yield of a rice crop after three cropping systems, rice-wheat, rice-pea-rice, and rice-sugarcane-ratoon-wheat/fallow. *E. crus-galli* was the dominant grassy weed after the rice-wheat and rice-pea-rice sequence, but it was completely suppressed after the sugarcane sequence. Among sedges, *F. miliacea* was dominant after rice-wheat and *C. difformis* after

rice-pea-rice. After the sugarcane system, *C. rotundus* became the main weed. The yield loss due to weeds was highest after the rice-wheat system, followed by the rice-pea-rice and sugarcane systems. Under farmers' weed management practices, yield losses due to weeds ranged from 13.1% to 22.4%, which need to be reduced by improved weed management practices.

The Indo-Gangetic Plains (IGP) are spread over Sind, Punjab, Baluchistan, and part of the Northwest Frontier Provinces of Pakistan; Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal states of India; the southern Tarai of Nepal; and Bangladesh (Ali and Pande 1999, Woodhead et al 1994). The climate of the IGP is continental monsoon type with hot summer season and cool winter. Temperature extremes are recorded in the west but are mild in the east. Most of the rainfall (around 85%) is received during the summer (June-September). Rainfall is very low in the western part (400–600 mm) and increases toward the east, which receives heavy rain (up to 1,800 mm). Only occasional showers are received during winter. Soils are mainly alluvial in nature as a result of the deposition of the Indus and Ganga River systems. These are primarily calcareous and micaceous alluviums with sandy loam to loam in the upper reaches and becoming fine textured in the distal plains close to the mouth of the river systems. Agriculturally, this region is highly productive and contributes substantially to the food security of the component countries. Rice and wheat are the predominant cereals often grown in sequential cropping under irrigated conditions. Sugarcane, cotton, and potato are the major commercial crops. Important food legumes include chickpea, lentil, pea, pigeonpea, groundnut, urdbean, mungbean, and cowpea, but the area under these crops has declined sharply over the years and these are generally grown on marginal land on rainfed area in diverse cropping systems (Ali et al 2000).

Characteristics of the IGP and cropping systems

There is a large spatial variation in the physiographic, climatic, edaphic, and socioeconomic production factors of the IGP. In the western parts, infrastructure of irrigation, input supply, markets, and farm mechanization are better developed than in the eastern region. In the west, groundwater is overexploited, whereas, in the east, it is underused. Population pressure increases toward the east, resulting in smaller and fragmented holdings. Farmers in the east are less enterprising and poorer, with less capacity to bear risk. Wages for labor are low and labor is more readily available. Based on these factors and constraints, the IGP can be divided into five transects (Gupta et al 2002, 2003, Gupta 2003, Hobbs and Gupta 2003). GIS analysis of cropping systems of the IGP has been done by Pande et al (1999).

Transect 1. Trans-Gangetic Plains of Punjab (Pakistan)

This is a semiarid region with 400–800 mm annual rainfall, 85% of which is received between June and September. Temperature in summer exceeds 45 ºC. Soils are alluvial, calcareous, and course to medium fine textured with alkali soils in stretches. These are sloping with good drainage. The entire area is fully irrigated. The main cropping system is rice-wheat and the major cash crop is cotton. In Punjab, where Basmati rice is predominantly grown, late harvesting delays wheat sowing. In Sindh Province, coarse rice is generally grown and here waterlogging and high soil moisture at the time of rice harvest delay wheat sowing. Wheat yields are therefore low in Pakistan.

Table 1. Area under different cropping systems in the states of Punjab and Haryana.

Cropping system	Area (000 ha)	
	Punjab	Haryana
Rice-wheat	1,750	867
Cotton-wheat	242	603
Maize-wheat	492	21
Pearl millet-mustard	–	321
Pearl millet-wheat	–	209
Sorghum-wheat	–	121
Sugarcane-ratoon-wheat	5	78
Green manure-potato-sunflower	15	–

Transact 2. Trans-Gangetic Plains of Indian Punjab and Haryana

The climate and physical features in this transact are quite similar to those of Transect 1, with 400–800 mm rainfall mostly between July and September. The topography is saucer shaped. The region is fully irrigated by canals and tubewells. The water resources are under severe pressure due to overexploitation of groundwater and a falling water table, which is increasing the cost of water pumping. Availability of local labor is limited and migrant labor is engaged for relatively high wages, particularly for rice transplanting. The cropping system is predominantly rice-wheat. In Punjab, the farming system is highly mechanized, input-intensive, and dependent on conjunctive use of surface water and groundwater. In Punjab, 33% of the area is canal irrigated and 66% is well irrigated. Fertilizer use is around 250 kg nutrient ha^{-1} $year^{-1}$. Rice is entirely transplanted and, for wheat, farmers have started practicing zero-tillage. Other summer crops are maize and cotton. Crops of minor importance are mustard, sunflower, potato, sugarcane, and maize + cowpea fodder. Mustard is mostly grown as an intercrop with wheat (Hobbs et al 1985). In Haryana, rice-wheat remains the first cropping system, followed by cotton-wheat. In drier areas, pearl millet is an important crop. Sorghum is grown exclusively for fodder. The area under different cropping systems as reported by Yadav and Subba Roa (2001) is given in Table 1.

Transect 3. Parts of Haryana, Tarai of Uttaranchal, western and central Uttar Pradesh, Tarai region of Nepal

The climate in this transect is hot and subhumid, with annual rainfall up to 1,400 mm, 75% of which is received during the monsoon season. Soils are alluvial with large saline and alkaline patches. In this transect, after rice and wheat, sugarcane is an important crop, used as a break crop between the rice-wheat sequence. Cropping systems are more varied here than in transect 2. Other important crops are pearl millet, maize, and pigeonpea in summer and mustard and chickpea in the winter season. Irrigation is delivered by an old canal system that was designed to meet irrigation requirements during the dry winter season. Wheat receives 3–5 irrigations and rice is irrigated during long periods without rain. The water table is declining. Farm mechanization is increasing and farmers with small holdings hire tractors for land preparation. Animal power is used in a very limited way. The important cropping systems practiced in Uttar Pradesh are rice-wheat (4.1 million ha), pearl millet-wheat (1.2 million ha), and fallow-wheat (0.9 million ha).

Table 2. Area under different cropping systems in the state of Bihar.

Cropping system	Area (000 ha)
Rice-wheat	1,511
Rice-fallow	1,554
Rice-*Lathyrus*/lentil/chickpea/pea	250
Rice-sugarcane	52
Sugarcane-rice-wheat	78
Maize-maize	63
Maize-wheat	47
Jute-rice	37

Transect 4. Eastern Uttar Pradesh, Bihar, and eastern parts of Nepal

The climate is hot and subhumid, with annual rainfall up to 1,500 mm. Compared to transects in the west, temperatures rise early in the east and the mean temperatures are higher for longer. This reduces the length of the growing season of wheat. The soils are medium to fine textured. Many low-lying flood-prone areas have drainage congestion. For this reason, rice is the dominant crop of summer and, in many areas, no crop other than rice can be grown in this season. Cropping in this transect is less mechanized, more labor intensive, and more diversified. Groundwater remains underused. Farmers use fewer inputs because of serious problems of drainage congestion and rain-water management (Velayatham et al 1999). Holdings are small and fragmented. Farmers diversify the rice-wheat system more to cover the risks of drought and flood-prone agriculture. Because of the paucity of irrigation, after rice, large areas are sown with chickpea, lentil, and pea, which have low yields. Much of the area remains fallow in the winter season. In uplands, pigeonpea, maize, and sorghum are sown in summer. In North Bihar, winter maize is popular for its high yields. Many farmers grow three rice crops in a year. Boro rice is becoming popular for its high yield. Winter maize and boro rice are fully irrigated. The area under different cropping systems followed in Bihar is given in Table 2.

Transect 5. West Bengal and Bangladesh

The climate is hot and subhumid, with annual rainfall up to 1,800 mm. Physical features are similar to those of transect 4 but with increased problems of drainage and floods during monsoon. Because of high population pressure, farm holdings are small and fragmented. Farms are highly diversified. Rice is the predominant crop. Wheat is not an important crop in this transect and hence the area under rice-wheat is limited. Vegetables are grown on a large scale. In the winter season, mustard is an important crop. Jute is also an important crop. In many areas, monoculture of rice, 2–3 crops of rice per year, is practiced. Boro rice is becoming popular. Important crop sequences, as reported by Yadav and Subba Rao (2001), are given in Table 3.

Weed flora of rice and wheat in the IGP

Weeds of rice

Weed species found in rice fields in the IGP are quite numerous and their presence may be seen throughout, though density may vary in different ecological regions. These include grasses, non-grasses, and sedges.

Table 3. Area under different cropping systems in West Bengal.

Cropping system	Area (000 ha)
Rice-vegetables	942
Rice-potato	462
Rice-wheat	233
Rice-mustard	358
Rice-jute	120
Rice-pulses-summer rice	18

Grasses: *Echinocloa crus-galli*, *E. colona*, *Leptochloa chinensis*, *Ischaemum rugosum*, *Paspalum distichum*, *Cynodon dactylon*.
Broadleafs: *Ammania baccifera*, *Ludwigia hyssopifolia*, *L. adscendens*, *Caesulia axillaris*, *Commelina benghalensis*, *C. diffusa*, *Cyanotis axillaris*, *Eclipta alba*, *Corchorus* spp.
Sedges: *Fimbristylis miliacea*, *Cyperus difformis*, *C. iria*, *C. rotundus*.

Direct-seeded rice faces a potential threat from changes in the competing weed flora, with an increase in those species that are difficult to control (Johnson et al 2003). These include *I. rugosum, E. crus-galli, E. colona, L. chinensis,* and *Cyperus* spp.

Weeds of wheat

These are *Phalaris minor*, *Coronopus didymus*, *Melilotus* spp., *Vicia sativa*, *Lathyrus aphaca*, *Chenopodium album*, *Anagallis arvensis,* and *Polygonum* spp.

In wheat fields, the most dominant and problematic weed is *P. minor* (Little seed canary grass). Broadleaf weeds are easy to control, but *P. minor* has developed resistance to isoproturon, the commonly used herbicide against it, and new herbicides are recommended for its control. The infestation of *P. minor* and also the development of resistance against isoproturon are more noticed in the western IGP, particularly in the state of Haryana (Malik 2003).

The important weed species of rice vary according to the different regions of the IGP. The density of weeds recorded in rice fields under the rice-wheat rotation in different regions of the IGP is shown in Figure 1. In the western IGP, at Pantnagar (transect 3) in unweeded fields of transplanted rice at 56 DAT, the dominant weeds in terms of plant density were *Caesulia axillaris* (33.4%), followed by *Echinochloa colona* (22.6%), and, in terms of biomass, the grass weed *E. colona* (55.0%) accounted for more than half of the weed growth, followed by *Cyperus difformis* (21.1%). In eastern Uttar Pradesh at Kumarganj (transect 4), similar observations were made at 60 DAT. *Cyperus rotundus* was dominant (40.0%) in terms of numbers, followed by *Cynodon dactylon* (25.4%), but, in dry weight of weeds, *E. colona* contributed 54.5%, followed by *Cyperus rotundus* (26.0%). Further east, at Bikramganj (Bihar) and also in transect 4, *Ludwigia* species dominated in number (80.5%) as well as in biomass (68.4%), followed by *C. rotundus* in density (12.1%) and biomass (25.1%).

Weed flora in rice under different cropping systems—a case study

In the Uttaranchal plains, the two dominant cropping systems are rice-wheat and rice-sugarcane-ratoon-wheat/fallow (Singh and Singh 2004). Rice-pea-rice is increasingly popular because of the high economic returns from pea raised for green pods and summer rice, which has high yield (8–10 t ha^{-1}). A study of these three cropping systems was made to determine their effect on weed density

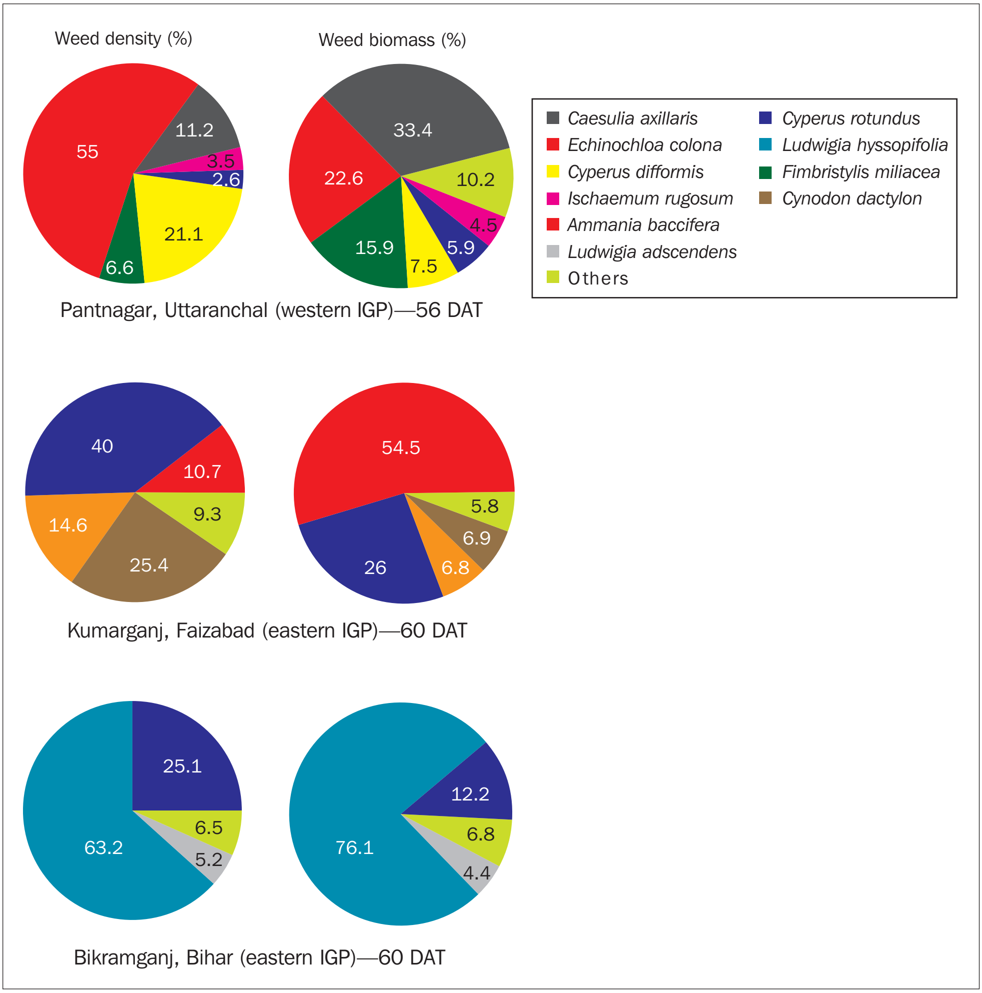

Fig. 1. Density and dry weight of weeds in an unweeded rice field under the rice-wheat cropping system at different sites in the IGP (west to east).

in the rice season. Fifteen fields under these three cropping systems were identified in different villages. In each field, after rice transplanting, two quadrats of 3 × 3 m each were marked. Within each quadrat, subplots of 1 × 1 m were marked and maintained as weedy checks and the remaining area was hand weeded at weekly intervals to keep it free from weeds. The rest of the field was used as under the farmers' practices. For each situation, observations were made on weeds and rice yield.

Weed density and dry weight

Observations on the weed density (number of different weed species m^{-2}) and dry weight of weeds in weedy plots were recorded at 56 DAT. Large variations occurred in weeds under different cropping systems. Among the sedges, *C. iria* was prominent in rice fields under the rice-pea-rice system (Table 4). Its density was lowest in the sugarcane system, followed by the rice-wheat system. *C. difformis* was prominent in the rice-wheat and rice-pea-rice systems and totally absent in the

Table 4. Density (no. m^{-2}) and dry weight (g m^{-2}) of sedges in unweeded rice plots after different cropping systems at 56 DAT.

Species	Rice-wheat		Rice-pea-rice		Rice-sugarcane	
	Density	Dry wt.	Density	Dry wt.	Density	Dry wt.
Cyperus iria	5.2	7.3	18.4	27.6	2.5	3.6
C. difformis	22.5	37.9	26.0	41.5	0.0	0.0
C. rotundus	8.5	7.0	8.4	12.7	59.7	16.7
Fimbristylis miliacea	73.0	85.6	16.5	28.9	7.0	13.7

Table 5. Density (no. m^{-2}) and dry weight (g m^{-2}) of grasses in unweeded rice plots after different cropping systems at 56 DAT.

Species	Rice-wheat		Rice-pea-rice		Rice-sugarcane	
	Density	Dry wt.	Density	Dry wt.	Density	Dry wt.
Echinochloa colona	14.4	17.3	7.5	99.3	1.2	0.9
E. crus-galli	22.5	62.2	26.9	67.9	1.5	1.2
Ischaemum rugosum	2.4	20.8	0.0	0.0	0.0	0.0
Digitaria spp.	1.3	0.9	0.0	0.0	0.0	0.0
Leptochloa chinensis	8.1	14.8	0.0	0.0	6.1	4.8

Table 6. Density of nongrasses (no. m^{-2}) in unweeded rice plots after different cropping systems at 56 DAT.

Species	Rice-wheat	Rice-pea-rice	Rice-sugarcane
Eclipta alba	2.9	1.1	0.0
Commelina benghalensis	4.0	1.1	1.0
Alternanthera sessilis	0.0	41.1	0.0
Parthenium hysterophorus	0.0	0.0	0.5
Cyanotis axillaris	0.0	2.5	0.0

sugarcane system. In contrast, *C. rotundus* was dominant in the sugarcane-based system. Population and dry weight of *F. miliacea* were very high in the rice-wheat system, followed by the rice-pea-rice system, and much lower in the sugarcane system. Among grasses, density and biomass production were highest for *E. colona* and *E. crus-galli* (Table 5). *E. colona* was dominant in the rice-pea system, whereas *E. crus-galli* dominated in the two systems without sugarcane. *I. rugosum* and *Digitaria* spp. were present only in the rice-wheat system. *Leptochloa* was completely absent in the rice-pea-rice system but present in the other two systems. Overall, sugarcane in the cropping system checked weed growth in the following rice crop. The density of broadleaf weeds was quite low except for *Alternanthera sessilis,* which was present at a density of 41.1 m^{-2} in the rice-pea-rice system (Table 6).

Relative weed density and biomass of different weed types (sedges, grasses, and broadleafs) were compared under weedy conditions and farmers' weed management practices for all three cropping systems. In the rice-wheat system, weed density was highest for sedges (>60%), followed by grasses and broadleafs, but, in biomass, grasses had a >60% share, followed by sedges and nongrasses (Fig. 2). Relative weed density and biomass had a similar trend in both the weedy and farmers'-managed plots. Thus, in the rice-wheat system, grasses would cause maximum harm to the rice crop. In the rice-pea-rice system, the relative density of different weed types in weedy plots was of nearly the same order, but, under farmers' practices, density of grasses was higher (50% of the total), followed by sedges and broadleaf species. In biomass, grasses were very dominant, contributing 71.5% of the dry weight under weedy conditions and 83.3% under farmers' practices. Thus, grasses were the most damaging weeds in the rice-pea-rice system, even more than in the rice-wheat system. In the rice-sugarcane system, grasses were checked. Here, sedges were dominant in number: in weedy plots, they numbered 50.1% of the total weed population, whereas, under the farmers' practice, they numbered 67.7% of the total weeds. Next in number were broadleaf weeds, whereas there were few grasses. In biomass, under weedy conditions, broadleaf weeds contributed the maximum (47.1%), followed by sedges (34.0%) and grasses (18.9%). Under farmers' practices, biomass of broadleaf weeds was only 33.6%, whereas that of sedges was 37.4%. Thus, under farmers' weed management practices, control of broadleaf weeds was better.

Rice yield

Rice yield under weed-free conditions was highest (5.89 t ha^{-1}) in the rice-pea-rice sequence, followed by the rice-sugarcane and rice-wheat sequences (Fig. 3). Under farmers' practices, rice yield under the three cropping systems was around 4.5 t ha^{-1}. In the weedy check treatment of the rice-pea-rice and rice-sugarcane systems, rice yield was very close, but, in the rice-wheat system, rice yield in the weedy check was lowest (2.81 t ha^{-1}). The yield loss caused by weeds in weedy plots was highest (47.2%) after the rice-wheat sequence, followed by the rice-pea-rice (42.4%) and rice-sugarcane (34.9%) systems (Fig. 4). In farmers' management, yield losses caused by weeds varied from 13.1% in the rice-sugarcane system to 22.4% in the rice-pea-rice system. Under improved management, rice yield can be raised by 16.4% in the rice-wheat system and by 22.4% in the rice-pea-rice system. The study brings out important differences in weed flora in the rice crop under different cropping systems, which will have implications for weed management. The rice-sugarcane system suppresses weed growth, particularly the growth of grassy weeds. Rice yield can be raised by improving farmers' weed management practices.

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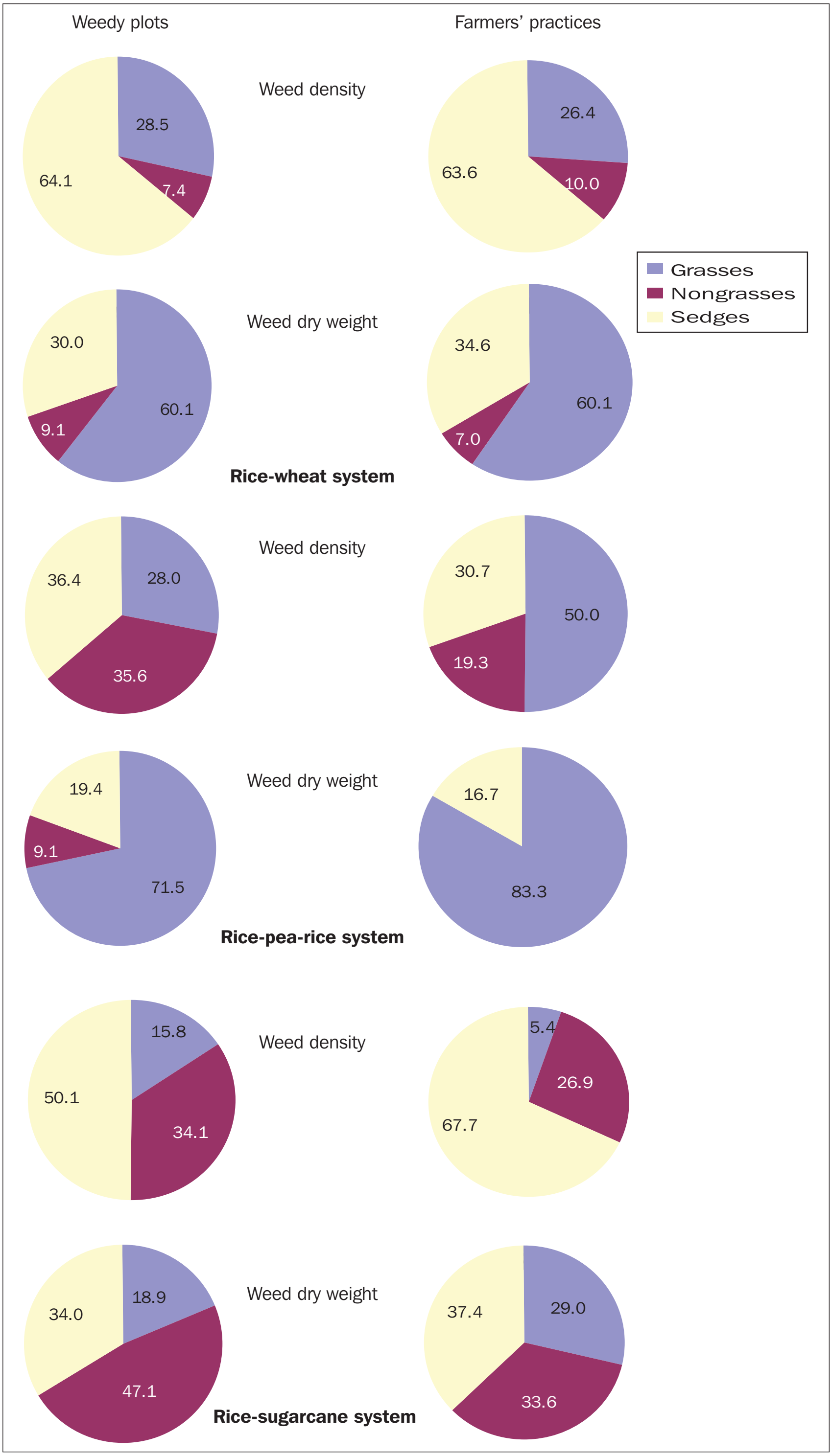

Fig. 2. Relative weed density and dry weight of weeds 56 days after transplanting in different systems.

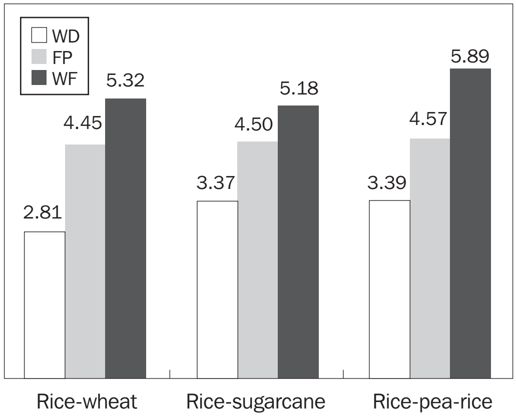

Fig. 3. Rice grain yield (t ha^{-1}) in farmers' fields after different cropping systems. FP = farmers' practice, WF = weed free, WD = weedy plots.

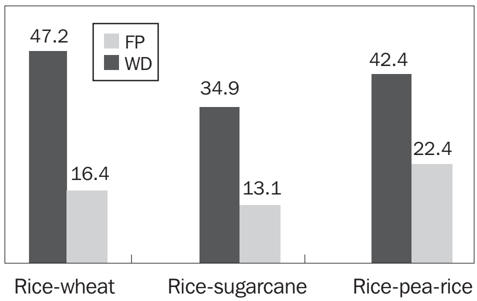

Fig. 4. Rice grain yield loss (%) under different cropping systems. FP = farmers' practice, WD = weedy plots.

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Notes

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Rice-growing environments in Bihar and prospects for direct seeding

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In Bihar, rice is grown in three seasons: spring (October-November to May), summer (March to early July), and *kharif* (May-June to October-December). Spring and summer rice are transplanted and grown under irrigated conditions. These rice crops are relatively productive though they occupy only 0.2 and 0.07 million ha, respectively. The majority of the rice area is cultivated in the kharif season on lands with varying toposequences—upland, medium land, lowland, and deepwater and flood-prone areas (*dhab*, *diara*, and *tal* land) by direct seeding or transplanting under rainfed as well as irrigated conditions. In medium lands and lowlands of Bihar and uplands of north Bihar, rice is usually established by transplanting while in other situations it is grown under direct-seeded rainfed conditions. To make rice growing more profitable, the adoption of direct seeding in place of transplanting appears an attractive option. There is a wide scope for introducing direct-seeded rice in transplanted-rice areas by adopting suitable varieties and weed management practices.

This paper discusses the features of various rice-growing ecosystems, and methods of tillage, varieties grown, rice establishment methods, weeds and weed control, and other agronomic practices followed by farmers under varying rice-growing environments. The areas in which the replacement of transplanting by direct seeding of rice is feasible have also been identified and indicated for future action.

Rice is grown on about 5.13 million ha, with an average rice yield in the state of 1,543 kg ha^{-1}. Based on rainfall, temperature, terrain, and soil characteristics, Bihar State is broadly delineated into three agro-climatic zones (Table 1). By zone, the largest area is in zone III (1.53 million ha), followed by zone I (1.32 million ha) and zone II (0.75 million ha). Zones IIIA and IIIB have 0.31 and 1.22 million ha, respectively, under rice. The average rice productivity in zones I, II, IIIA, and IIIB is 1,392, 1,241, 1,353, and 1,940 kg ha^{-1}.

Table 1. Characteristics of the agro-climatic zones of Bihar.

Zone	Characteristics
Northwest alluvial plains (zone I)	Tropical humid to subhumid climate, 1,211 mm average annual rainfall, monsoon breaks in mid-June, soils light- to medium-light-textured, mostly calcareous, Ca-induced Fe and Zn deficiency, moderately rich to poor in N, medium to very low in P, and medium to high in available K, westerly wind with dust storms in April-May, *chaur* (waterlogged) and *diara* (flash-flood-prone) land also present.
Northeast alluvial plains (zone II)	Humid to subhumid climate, 1,405 mm average annual rainfall, monsoon breaks between last week of May and first week of June, soils light- to medium-textured and moderately acidic to neutral, high water table, waterlogging, Fe and Zn deficiency and Mn toxicity, poor in N, poor to medium in available P and K, *chaur* and *diara* land also present.
South Bihar alluvial plains (zone IIIA and IIIB)	Subhumid climate, drier than zone I and zone II, 1,110 mm average annual rainfall, monsoon breaks in third week of June, medium- to heavy-textured soil, moderately well drained to poorly drained (impervious layer), moderately acidic to slightly alkaline, *tal* and *diara* land and hilly tracts also present.

Rice ecosystems

Rice is grown in upland, medium land, lowland, and deepwater areas. The characteristics of these ecosystems are as follows:

- *Upland*. This is rice land where water does not stagnate even after heavy rains. It is situated at the top of the toposequence and soils are light in texture with poor water-holding capacity. Typical drought-prone upland situations mostly exist in the southern portion of zone IIIA and are distributed partly or wholly in Baunsi, Banka, Katoria, Chanan, Barahat, and Belhar blocks in Banka District; Lakshmipur, Jhajha, Chakai, Sono, Khaira, Jamui, and Sikandara blocks in Jamui District; and Ariari block in Shekhpura District. The uplands of north Bihar have more favorable conditions and tend to be more productive. In uplands, early rice varieties (75–105 d duration) are generally grown.
- *Medium land.* This is defined as rice land where flooding up to 25 cm occurs for some period and where drainage facilities are needed. This land is mostly confined to canal-irrigated systems and also around tubewells. Medium land has the highest rice productivity and high-yielding varieties (130–135 d) are predominant.
- *Lowland.* Flooding occurs up to 50 cm and drainage is not usually feasible. Broadly, it can be divided into two major types: (1) favorable lowland, where photo-insensitive long-duration (150–155 d) high-yielding varieties are grown, and (2) unfavorable lowlands in which photosensitive tall indica traditional rice varieties are grown, which initially may suffer from drought and later from flood. This ecosystem predominates in north Bihar.
- *Deepwater*. These are low-lying areas where flooding is more than 50 cm for long periods and they are classified as deepwater areas and locally called *chaur*. The drainage of water is not possible. There are three types of deepwater areas: (1) shallow deepwater area in which water depth goes up to 1.0 m, (2) medium deepwater with depth up to 2.0 m, and (3) typical deepwater or floating-rice areas where water depth goes up to 3.5 m. Varietal requirements for these situations are different. *Chaur* lands are confined to north Bihar and cover 0.54 million ha.

Flood-prone land. Apart from unfavorable lowlands and deepwater areas, rice grows in several other flood-prone areas: (1) flash-flood-prone areas, (2) *dhab* land, (3) *diara* land, and (4) *tal* land.

Flash-flood-prone areas. Along the state's northern border in West Champaran District, a thin strip of rice land situated along the courses of numerous rivers and streams originating in the Himalayas (Mainatar area) is prone to a peculiar type of flash flooding. Newly transplanted rice hills get uprooted or the growing rice crop is made to lodge by gusty water flowing from rivulets. The period of flooding is very short.

Dhab land is a flood-prone area situated adjacent to rivers. The soils of *dhab* land are stable, unlike *diara* land, which is subject to frequent erosion and deposition processes of rivers. After a long time, rivers may change their courses and come closer to *dhab* land and cause erosion of stable land. The flooding pattern is similar to that of *diara* land.

Diara land is a flood-prone area formed by meandering, braiding, and course changing of perennial rivers. This land is situated in between the natural levees that get inundated for different periods of time and are periodically eroded. It may be formed in between two courses (*dhars*) of the same river as an island.

Diara land in Bihar occupies nearly 1.13 million ha distributed in the basins of the rivers Ganga (0.51 million ha), Gandak (0.14 million ha), Burhi Gandak (0.22 million ha), Sone (0.11 million ha), and Kosi (0.15 million ha). The nature and properties of *diara* soils are invariably prone to change because of the deposition of sediments during flooding. The soil texture is heavier with the increase in distance from the river bank. Topographically, *diara* land can be divided into three categories: upland, medium land, and lowland. Upland *diaras* are flooded not more than a month in late August or September and that, too, only in years of high flood. These areas are suitable for crop production almost all year-round. Medium lands remain flooded for more than a month. They are flooded almost every year and water depth may not be more than 30–45 cm. Crop production activities are disrupted for only 2–3 months. Lowland *diaras* are inundated for more than 3 months every year and water depth may be more than 1 m. Only 5–7 months are available for cultivation.

The Ganga *diara* has three cropping seasons: (1) early *kharif* (May-June to mid-August), (2) early *rabi* (mid-September to mid-December), and (3) rabi (November to April). Rice is grown in early kharif in a limited area.

In Gandak *diara*, floods usually occur two or three times. The first flood is of shorter duration (3–4 d) in early August but the second is of 8–10 d around mid-August. The last flood from the last week of August to early September is of longer duration (up to 10–15 d) and is most devastating. Sometimes, it either does not occur or is mild.

Tal land. South of the natural levee of the Ganges River is a vast stretch of backwaters known as *tal* lands. They are saucer-shaped and remain inundated for 2–4 months during the rainy season. Soils are gray to dark gray in color, medium to heavy in texture, remain bone dry in summer, and crack heavily. *Tal* lands are spread over 96,600 ha, mainly in five districts of Bihar—Patna, Nalanda, Lakhisarai, Munger, and Bhagalpur. Generally, one crop during the rabi season is grown with very high yields. In fringes of *tal* land, however, direct-seeded or transplanted rice is grown in a limited area during the kharif season.

Rice-growing seasons

There are three distinct rice-growing seasons, summer (*garma*), kharif (*aus*, autumn, and *agahani*), and spring (*boro*) in Bihar.

Summer season

In this season, rice is grown under transplanted conditions on irrigated medium lands. Seeds are sown in March and the crop is harvested in early July after the onset of monsoon. The area under summer rice has shrunk, however, because of irrigation problems (erratic supply of electricity and increasing cost of diesel) and has dropped to around 70,000 ha. Sometimes, continuous rain at maturity also poses problems in harvesting, threshing, and drying. Summer rice is now mainly confined to the Triveni canal system and mini-command areas of tubewells spread over various parts of the state.

Kharif season

This is the main rice-growing season. The time of seeding, varieties, and establishment methods differ according to land situations. Rice may be direct-seeded from March to June. Seeds for transplanted rice are sown from the last week of May to June. Aus (*bhadai*) and autumn rice varieties are photo-insensitive and are grown in upland and medium land. In favorable lowland, photo-insensitive high-yielding varieties are generally grown, whereas, in poorly drained lowlands and deepwater areas, tall indica photoperiod-sensitive rice is grown.

Spring (boro) season

Boro rice is grown on about 0.2 million ha in Saharsa, Araria, Madhubani, Purnia, Katihar, Kishanganj, and East and West Champaran districts in north Bihar. Seeds are generally sown in October-November and seedlings are transplanted in January-February. The crop matures in May. The highest productivity of rice is achieved in this season. Boro rice is most suited for those areas where waterlogging does not permit cultivation of rabi crops.

Rice-based cropping systems in Bihar

There is wide variation in rice-based cropping systems because of the vast differences in topographic features in the state. The most prevalent rice-based cropping systems appear in Table 2.

Methods of rice culture

The methods of rice culture vary widely in Bihar, according to season and topography. The following section presents the methods of rice culture adopted by farmers under varying situations.

Summer rice

1. *Varieties*. Short-duration varieties—Pusa 2-21, Pusa 33, CR 44-35 (Saket-4), and Prabhat—are generally grown. These varieties take 120–125 d to mature (15 d more than in the kharif season) because of cold at the nursery stage. On saline soils, variety NC 1626 performs well and has weed-smothering ability.
2. *Raising of nursery*. Seeds are sown in a well-prepared and fertilized nursery bed by the dry method in light-textured soils of north Bihar and by the wet method in heavy-textured soils. They are ready for transplanting after 30–35 d because of the slower growth rate at prevailing low temperature.
3. *Tillage and stand establishment.* After harvest of rabi crops, land is plowed by a soil-turning plow and then by a cultivator to destroy weed seedlings. Rice is transplanted randomly, keeping 15–20-cm spacing between hills.
4. *Fertilizer application.* The crop responds to a higher dose of nutrients (100 kg N + 50 kg P_2O_5 + 25 kg K_2O ha^{-1}) in this season. In calcareous soils of north Bihar, Zn-deficiency

Table 2. Predominant rice-based cropping systems in Bihar.

Land situation	Ecosystem	Cropping system adopted
Upland		
Typical	Rainfed	Rice-fallow
Favorable	Irrigated	Rice-wheat/winter maize/winter maize + potato/potato/rape and mustard/sugarcane/tobacco
Medium land	Irrigated	Rice-wheat/winter maize/ potato/sugarcane/rape and mustard
	Rainfed	Rice-lentil/lathyrus/linseed/gram
Lowland		
Favorable	Irrigated	Wheat/winter maize/spring maize/sugarcane
Unfavorable	Rainfed	Wheat/jute/sugarcane/mungbean
Deepwater		
Shallow (0.5–1 m)	Rainfed	(a) Rice-mungbean/sugarcane (b) Rice + mungbean/foxtail and proso-millet/ sesame/jute/fodder sorghum-fallow
Medium (1–2 m)	Rainfed	Rice-fallow
Typical (>2 m)	Rainfed	Rice-fallow
Diara land (Gandak River)	Rainfed	Rice-lathyrus/lentil/wheat/sugarcane
Tal land	Partially irrigated	Rice-wheat
	Rainfed	Rice-lathyrus/lentil/linseed/lentil + linseed

symptoms at the seedling stage appear and this can be remedied by a spray of 0.5% $ZnSO_4$.

5. *Irrigation.* About 10–12 irrigations are required. The frequency of irrigation increases with the advancement in crop age. A hot westerly wind in May increases evaporative demand sharply.
6. *Weeds and weed control.* The most common weeds are *Cyperus rotundus*, *Echinochloa colona,* and *Cynodon dactylon,* which are controlled by manual weeding.
7. *Insect pests and diseases.* There is not much problem of insect pests and diseases in this dry season. The attack of *gundhi* bug (*Leptocorisa acuta*), however, takes place at the milk stage. Dusting with methyl parathion 2% dust or quinalphos 1.5% dust at 25 kg ha^{-1} reduces damage from the gundhi bug.
8. *Harvesting.* The crop is harvested manually by the first week of July. It yields around 4–4.5 t ha^{-1}. The second crop of rice is usually grown on land vacated by summer rice.

Kharif rice

Kharif rice is grown under varying land situations—upland, medium land, lowland, deepwater, and flood-prone *dhab*, *diara,* and *tal* land. Rice is established by both transplanting and direct-seeding methods in these situations, except on medium land, on which transplanting is the sole method of stand establishment.

The methods of raising seedlings for transplanting in upland, medium land, and lowland are similar except for the difference in sowing date. Seeds of long-duration varieties (145–155 d) are sown in a nursery bed from 25 May to 7 June, medium-duration varieties (130–135 d) from 1 to 15 June, and short-duration varieties (105–110 d) from 15 to 30 June. Some farmers in the Sone River command area in Rohtas District prefer to grow seedlings late, that is, in the last week of

June. They believe that in a late-sown nursery the incidence of insect pests [mealy bug (*Brevennia rehi*) and brown planthopper, BPH] and diseases (sheath blight and false smut) is less.

Seedlings are raised by the dry- and wet-bed methods. In the former, seeds soaked overnight or simply moistened are drilled in moist soil behind a country plow or simply broadcast and mixed with soil by a tractor-drawn cultivator and a light planking is given. Generally, the nursery area is one-tenth of the area to be transplanted. This method is prevalent in light-textured soils of the north Bihar alluvial plains.

The problems encountered while raising seedlings by the dry-bed method under rainfed situations are

1. Development of a crust on the soil surface because of rains soon after sowing, leading to poor seedling emergence.
2. Seedling mortality because of moisture stress.
3. Iron and zinc deficiencies in seedlings in calcareous soil.
4. Excessive weeds (*C. rotundus* and *E. colona*).

In the wet-bed method, soaked or moistened seeds are broadcast on puddled soils having a thin layer of water. The excess standing water is drained out after 24 h. Seedlings are raised on 0.05 ha for transplanting 1 ha. This method is practiced in heavy soils of the south Bihar alluvial plains. In canal-irrigated areas, some farmers use only 15–20 kg of seed for the nursery meant for 1 ha of transplanting vis-à-vis the normal practice of 40–50 kg of seed. The lower seed rate results in the production of robust seedlings with 1–2 tillers, enabling transplanters to place one seedling per hill.

Upland rice

Varieties. In typical uplands composed of high hilly tracts and poor lands of Khaira, Sono, and Chakai plateau areas in south Bihar, very early rice called *sathi* matures in 60–70 d and occupies the largest area. The crop is sown in June. The crop matures by the time rains cease. Weeds are the main problem. In other upland areas, varieties of slightly longer duration (around 100 d) are grown.

The upland rice in north Bihar is grown under transplanted and partially irrigated conditions. High-yielding early varieties Pusa 2-21, CR 44-35 (Saket-4), and Prabhat (100–105 d) and Saroj (115 d) are recommended for cultivation. However, farmers prefer to grow variety Parmal, which has good grain quality, drought tolerance, and weed-smothering ability apart from fairly good and stable yield. In some areas, tall-statured local variety Hathijhulan possessing drought tolerance and weed-smothering ability is also grown.

Tillage and stand establishment method. After the harvest of rabi crops in north Bihar, land is plowed twice or even three times during summer to control weeds. Since water does not stagnate after rains, puddling is done after bunding the field by spade and impounding irrigation water. Some farmers finally plow the land with a soil-turning plow and allow irrigation water to come in. When land becomes fully saturated, planking is done twice to obtain a desirable puddle for transplanting.

Cultivation of upland and medium land can control *Cyperus rotundus* as the weed is inverted and the tubers are raised to the surface and subsequently do not create much of a problem. Some poor farmers simply make holes with a bamboo-stick when the soil becomes saturated after rain and transplant seedlings in these holes. The crop is grown mostly under rainfed situations. One or two life-saving irrigations may be given when drought occurs.

Weeds and weed control. Major weeds in uplands are *C. rotundus, E. colona, C. dactylon, Caesulia axillaris, Commelina benghalensis*, and, in some areas, *Trianthema monogyna*. Weeds are removed manually 25–30 d after transplanting when the soil is under aerobic conditions.

Insect pests and diseases. Gundhi bug attack at the "milk stage" of rice is common. Brown leaf spot and bacterial leaf blight are common diseases.

Harvesting. The crop is harvested in early October, vacating the land for the timely sowing of oilseeds, pulses, potato, and winter maize. Grain yield varies from 3 to 3.5 t ha^{-1}.

Medium-land rice

This is grown exclusively by the transplanting method under fully/partially irrigated and rainfed conditions.

Varieties. High-yielding medium-duration (125–135 d) varieties IR36, Kanak, Sita, Rajendra Dhan-201, Sujata, and Rajendra Shweta; long-duration (145–155 d) varieties Rajshree, Jayshree, Mahsuri, Rajendra Mahsuri-1, and Satyam; and improved variety BR34 have been recommended for cultivation. However, varieties MTU 7029, called Nati Mahsuri, BPT 5204 (Super Mahsuri), Sonam, and Lal Sita have occupied the largest area, especially in south Bihar, as farmers choose high-yielding varieties with superior grain quality for fetching a better price after being converted into parboiled or *arwa* rice.

Tillage and stand establishment. Tillage operations differ widely in light-textured soils of north Bihar; 2–3 summer plowings from April to June are necessary to limit weeds. In the south Bihar plains, summer plowing is not done on heavy-textured soils. After rainfall in May-June, weeds start growing fast. Land is cultivated giving one or two passes in moist or standing-water conditions 8–10 d before final puddling to destroy some weeds. At final puddling, land is plowed by a cultivator (2–3 passes), followed by planking. Weeds, especially *C. dactylon*, are pulled out manually before transplanting.

There is wide variation in the number of seedlings per hill. Usually, 4–5 to 8–10 seedlings $hill^{-1}$ are transplanted vis-à-vis the recommended practice of 2–3. Recently, some farmers of the Sone command area have started transplanting only 1 seedling $hill^{-1}$ of long-duration varieties. They claim lower incidence of BPH and sheath blight with this method. Perhaps less overcrowding of tillers (as they emerge at narrow angles, keeping some space among themselves) hinders the outbreak of pests and diseases. Bunch transplanting provides a congenial environment for them.

Weeds and weed control. The weed flora in medium-land rice differs in north and south Bihar. To some extent, *C. rotundus, E. colona, C. axillaris, Fimbristylis miliacea, C. dactylon,* and *Ammania baccifera* are found in both regions. However, the intensity of *Dactyloctenium aegyptium, E. crus-galli, Commelina nudiflora, Sphenoclea zeylanica, Ludwigia adscendens, L. hyssopifolia, Cyperus iria, C. difformis,* and *Monochoria vaginalis* is higher in the south Bihar plains, which comparatively enjoy higher soil wetness. Weedy rice is also becoming a serious problem in south Bihar. Weedy rice seedlings are carried over to the main field from the nursery bed along with cultivated rice seedlings and shattered seeds of weedy rice also germinate in the main field. Weedy rice and other weeds are pulled up within 20–25 DAT. Weedy rice is again removed before heading by cutting from the ground level. Where an alternate drying-and-wetting cycle exists in the rice field, as in north Bihar, weeds are removed 25–30 DAT manually by a *khurpi* (a kind of hand shovel).

Insect pests and diseases. Brown planthopper (*Nilaparvata lugens*) and mealy bug are the main insect pests in south Bihar. Green leafhopper (*Nephotettix* spp.), leaf folder (*Cnaphalocrosis medinalis*), and stem borer (*Scirpophaga incertulas*) are minor pests in both regions and the incidence of sheath blight and sheath rot is higher in south Bihar. Bacterial leaf blight and false smut are observed in similar intensity in both regions. Neck-rot incidence occurs mostly in north Bihar.

Harvesting. Medium-duration varieties are harvested by mid-November and long-duration varieties by the end of November and they yield around 4–4.5 and 4.5–5.0 t ha^{-1}, respectively. In command areas of the rivers Gandak and Kosi in north Bihar and those of Sone and Kiul-Badua-Chanan (KBC) in south Bihar and also around tubewells, rice yields are higher and more stable than in other ecosystems.

Lowland rice

Varieties. The major portions of lowland rice area are situated in north Bihar. High-yielding varieties Pankaj, Radha, Shakuntala, Satyam, and Kishori have been recommended for favorable lowlands, and improved varieties BR8, T141, and Vaidehi for unfavorable lowlands. Traditional variety Bakol is also popular among farmers because of its wider adaptability under rainfed transplanted/direct-seeded conditions.

Tillage and stand establishment. Land is plowed twice during the summer to destroy weeds. Rice is established by transplanting in favorable lowlands and by both transplanting and direct seeding in unfavorable lowlands.

In some lowlands of north Bihar, floodwater damage is common. To help ensure some yield during the kharif season, mixed cropping of long-duration rice with early maize (Tinpakhia, Nutan 101, etc.) is practiced. From 25 May to 7 June after rainfall, rice seeds (40 kg ha^{-1}) with early maize seeds (20 kg ha^{-1}) are broadcast after one pass on previously prepared land and then seeds are mixed with soil, giving a second pass, and finally planking is done. After manual weeding 25–30 DAS, 75 kg N ha^{-1} is topdressed after irrigation, if present. Maize is harvested within 70–75 days, generally before flooding, and rice is left alone and harvested by the end of November or early December, vacating the land for wheat cultivation. The maize and rice crops yield around 1.5 and 3.0 t ha^{-1}, respectively, if not damaged by flood.

Large areas on the flanks of rivers in north Bihar, particularly in east and west Champaran, Sitamarhi, Darbhanga, and Madhubani districts, may become suddenly inundated, leading to submergence of the rice crop. Such floods occur at least twice or three times in the wet season, causing severe damage to the rice crop. A majority of the farmers, however, do not want to take such a risk as they cannot afford to manage seedlings for replacement of crops completly damaged by flood. When the chances of flood have passed, two types of seedlings—conventional seedlings (brought directly from the first nursery) and *kharuhan* (seedlings uprooted from the first nursery and transplanted closely in the second nursery before final transplanting in the main field)—are used for transplanting; farmers use any photoperiod-sensitive varieties. Singh (1989) reported that varieties C 62-68 and Janaki were more suitable for double transplanting up to 16 September. Seventy-five-day-old kharuhan seedlings (30 d in the first nursery + 45 d in the second nursery) are more suitable than 30–75-d-old conventional and 60-d-old (30 + 30) kharuhan seedlings for transplanting (Singh and Thakur 1991). Transplanting of one kharuhan seedling $hill^{-1}$ at 15 × 10-cm spacing with 60 kg N and 20–40 kg P_2O_5 ha^{-1} has been found to be optimum for high yield (Singh et al 1989).

Fertilizer application. A fertilizer dose of 80 kg N, 40 kg P_2O_5, and 20 kg K_2O ha^{-1} for high-yielding varieties (HYVs) and a half dose for improved tall varieties have been recommended. However, farmers usually apply 30–35 kg N ha^{-1} twice to HYVs after the first weeding and at the boot stage and only once to photoperiod-sensitive tall varieties at the boot stage.

Weeds and weed control. The most common weeds in this ecosystem are *E. colona, C. iria, C. difformis, Chara corollina, Ipomoea reptense, C. diffusa, D. aegyptium,* and *Eichornia* *crassipes.* Weeds are removed manually before accumulation of rainwater. *Chara corollina*, a serious submerged aquatic weed in some areas, is collected by hand.

Harvesting. Long-duration HYVs are harvested by the end of November, whereas photoperiod-sensitive rice is harvested in the first fortnight of December, and these varieties yield around 4.0 and 3.0 t ha^{-1}, respectively.

Deepwater rice

Varieties. In shallow deepwater areas, traditional photosensitive varieties Bakoy (also called Bakol), Sahmardan, Gajpatti, Selha, and Dolang are grown. Improved varieties Janaki and Sudha have been released in the state, especially for this ecosystem. Traditional varieties Jagar, Pakhar, Sengara, and Darmi are cultivated in medium-deepwater rice areas. Varieties having good elongation ability, such as Desaria and Tengar, are grown in floating-rice areas.

*Tillage and stand establishment.*When land becomes plowable after drying of accumulated water in February-March, straw is collected from the rice field to facilitate tillage operations. The collected straw is burned in the field itself. The land is plowed (two passes), planked, and left as such for a fortnight or so to facilitate germination of weedy rice, locally called Jharang. After germination of weedy rice, the land is plowed and cross-plowed, and seeds are broadcast uniformly at 60–100 kg ha^{-1} and planking is done. Some farmers sow seeds by the dibbling method (locally called *chutaki*), putting 5–6 seeds in place by the khurpi while others drop a bunch of 5–6 seeds in place by hand at a desired distance in furrows opened by a country plow. These two methods, though laborious, are practiced to allow identification and removal of weedy rice. Some farmers, however, take out a small quantity of fresh cow dung in between the thumb and index finger and touch the seeds. About 4–5 seeds get adhered to the cow dung. Such lots are kept in the sun for drying. Seeds adhered to cow dung are then dropped manually in the furrows at about 20-cm distance. Farmers claim that this method, apart from helping in identifying and removing weedy rice, checks seedling mortality in the event of severe moisture stress and results in higher grain yield. Experiments conducted at Pusa in a shallow-deepwater area, however, showed that broadcasting, drilling, and dibbling methods of deepwater rice were statistically similar for grain yield.

There are certain deepwater areas in which water either dries quite late in the summer or does not dry at all. Rice sown late in June is likely to be damaged by flood because of early heavy rains. To save the crop from flood damage, farmers transplant 50–60-d-old seedlings of varieties able to elongate when the water depth drops down to an appropriate level in May-June. In this ecosystem, crabs can cause heavy damage to rice seedlings by cutting culms at ground level.

In shallow-deepwater areas, where seeding is possible in March, rice is grown in a mixed stand with any short-duration crop such as mungbean, sesame, proso-millet, foxtail millet, jute, and fodder sorghum. Mungbean is harvested within 65–70 d. Proso-millet and foxtail millet are harvested by early July. Jute and fodder sorghum are harvested by early August and then rice remains alone. Experiments conducted at Pusa (Bihar) revealed that mixed cropping of rice with sesame or jute was more profitable than other mixed-cropping systems (Pandey et al 1986). Experiments at Pusa (Bihar) showed that the cropping system involving a pure crop of mungbean (March to mid-June) followed by a pure rice crop (mid-June to December) had higher productivity and was more remunerative than mixed cropping of these two crops (Dwivedi 1997).

Weeds and weed control. The major problem in deepwater rice cultivation is the identification and timely removal of weedy rice. It is difficult to remove weedy rice entirely in the first weeding. Weedy rice possesses awns, matures earlier, and grains shatter appreciably at the time of harvest of cultivated rice. Weeds other than weedy rice are *E. colona, Ipomoea aquatica*, and *Corchorus* sp. In some areas of floating rice, *Eichornia crassipes* enters the field from outside with flowing water and gets deposited over rice plants. First weeding is done manually a month after sowing and weedy rice, *I. aquatica,* and *E. colona* are removed. Second weeding is done in July when water stagnates in the field. Weeds are cut away from the ground by a sickle (locally, the practice is called *chholani*).

Fertilizer. Where mungbean and rice are grown in a mixed stand, wood ash as per availability and 70 kg ha^{-1} diammonium phosphate are applied at sowing. However, topdressing of N at 20 kg ha^{-1} helps the rice plants achieve more height to escape submergence.

Pests and diseases. In floating-rice areas, the crop suffers from many pests such as stem borer, migratory birds, crabs, swimming rats, and wild boars (in some areas). Swimming rats, locally called *chhapka (Rattus norvegicus),* cut away the rice top from the water surface to make a shelter and eat away young panicles at the boot stage. Wild boars (*Sus scrofa*) dig in the soil after germination of seeds in search of roots of *Cichor* weed *(Cichorium intybus)* and in this way damage large areas because of seedling mortality.

Harvesting. The crop matures in December. Usually, rice panicles with 50–60-cm culms are harvested by sickle, leaving the remaining portion intact. In floating-rice areas, harvesting is done by boat. The crop yields 0.8 to 1.0 t ha^{-1}.

Diara land

Varieties. On fertile soil of the Gandak *diara*, photosensitive tall indica traditional rice varieties—Bakoy Gajpatti, Selha, Sahmardan, and Sugapankhi—are direct-seeded in May or are transplanted in late September on freshly deposited silts after floods recede. The first three varieties listed may tolerate complete submergence up to 7–8 days. On less fertile soils, however, local variety Katika is grown, which matures earlier and escapes drought at the reproductive stage.

Tillage and stand establishment. Rice is cultivated to a large extent in the Gandak *diara* and to some extent in Burhi Gandak and Ganga *diaras*. Direct seeding is the most prevalent method of stand establishment in the Gandak *diara*. Land preparation for direct-seeded rice starts in April after harvest of rabi crops (lathyrus, lentil, wheat, and sugarcane). After the first plowing (two passes), land is left exposed for drying of weeds. Second plowing is done 15–20 d later to kill germinated and reestablished weeds. Third plowing is done by a moldboard plow in May to uproot weeds from the deeper layer, followed by planking and collection of weeds. After 4–5 days, rice seeds at 60–70 kg ha^{-1} are broadcast on a dry seedbed and mixed with soil by a country plow (two passes) or by a cultivator. Planking is done in soils (silty loam) having adequate moisture for seed germination. In light-textured soil, land is left open, perhaps to save seeds from possible heat buildup after planking in the event of a very hot summer. Seeds germinate when summer rains fall.

Sometimes, heavy silt deposition takes place during floods from August to mid-September over uncultivated sandy soils or depressed pockets (locally called *mans*, *chharan*). Forty- to 60-d-old seedlings of photoperiod-sensitive traditional varieties are transplanted after flood recession in September in the Gandak *diara*.

Weeds and weed control. Weeds are the main problem in direct-seeded rice. They germinate in three phases: (1) soon after seeding, (2) after heavy rains in June, and (3) in September after recession of the last flood. *Cyperus rotundus, Echinochloa colona* (in lesser number), Rari (*Saccharum* spp.), and Narkat (*Phragmites karka*) germinate in the first phase. *E. colona* (in large numbers), *Fimbristylis miliacea,* and *C. dactylon* (in lesser number) germinate in the second phase. Narjor, Bhengraiya (*Eclipta prostrata*), Mokana, and Kukuraundha (*Blumea* sp.) germinate in the third phase.

The first weeding is done manually 20–30 DAS and the second at 40–45 DAS. Weeds germinated in the third phase are cut away from the ground by a sickle (the practice called *chholani*) around mid-October just before heading. This weeding does not help the rice crop much, but does help the succeeding lathyrus and lentil crops, which are sown by either broadcasting (*paira*) or dibbling with the help of a khurpi in the standing rice crop. On fertile soil, however, third weeding is not done as the succeeding wheat or sugarcane crops are grown after tilling the land.

Fertilizer. About 30 kg N ha^{-1} as urea is topdressed at the boot stage in both direct-seeded and late-transplanted rice as adequate residual soil moisture remains in the rice field.

Harvesting. All photoperiod-sensitive varieties are harvested in December. Variety Katika is harvested in November. The grain yield of direct-seeded rice varies from 2.5 to 3.0 t ha^{-1}, whereas late-transplanted rice yields 3.0 to 3.5 t ha^{-1}.

In the stabilized Ganga *diara*, transplanted rice is grown in certain pockets. Early and medium-duration high-yielding rice varieties are grown under partially irrigated conditions. In the periphery of abandoned *dhars* (low-lying pockets), early-maturing traditional rice varieties are grown in a mixed stand with early-maturing maize (*tulbulia*). Sowing is done in May after summer rain and the crop is harvested by mid-August before peak flood.

Dhab land

Since *dhab* land is situated adjacent to *diara* land, the pattern of flooding, tillage, rice establishment methods, varieties grown, and crop yields is similar, specifically in the Gandak *diara*. There tends to be less of a weed problem in *dhab* than in *diara* land and *E. colona, C. dactylon, C. rotundus,* and *Saccharum* sp. are the dominant weeds.

In the upper portion of *dhab* land, medium-duration rice varieties are grown under transplanted rainfed conditions. In the low-lying portion where floodwater accumulates to a higher depth, photoperiod-sensitive tall indica rice is grown under rainfed direct-seeded conditions.

There is not much problem of insect pests except for gundhi bug. In some areas, wild boars from adjacent *diara* land visit *dhab* areas in herds at night and eat rice panicles lying on the ground due to crop lodging.

Tal land

Tal land remains flooded during kharif; however, in fringes of *tal* land, where water depth at peak flooding does not reach 1 m, some farmers grow rice.

Varieties. In the uppermost portion of *tal* land, medium-duration (130–135 d) rice varieties Sita, Lal Sita, and PR 108 and long-duration (150–155 d) varieties Satyam, PBT 5204, and MTU 7029 are grown under both transplanted and direct-seeded conditions. Traditional rice variety Hathjhulan is the most popular for direct seeding. It possesses drought tolerance and gives fairly good yield at a low level of fertility. It is prone to lodging even at a moderate amount of fertilizer application.

Tillage and stand establishment. For transplanted rice, tillage operations are similar to those of other areas. For direct-seeded rice, land is plowed by a cultivator (two passes) after rains in May, followed by planking. This facilitates weed germination. Around mid-June, rice seeds at 60–80 kg ha^{-1} are broadcast and mixed with soil, giving two plowings without planking. Weeds uprooted during plowing are exposed to sun and subsequently dry. Seeds germinate either on residual moisture or after rains.

Weeds and weed control. The weed flora in rice grown on heavy-textured and flood-affected *tal* land differs from that in normal rice fields to some extent. The most common weeds of rice in *tal* area are Tentana (*C. iria*), Jaharmothi (*C. difformis*), Doob (*C. dactylon*), Kharsain (*E. colona*), Cana (*Commelina diffusa*), Jhirua (*F. miliacea*), Bhos (*Panicum repens*), Suruara (*Celosia argentia*), Vanshi/Garar (*D. aegyptium*), Farkanwa (*Cyanotis axillaris*), Bhirngi (*Alternanthera sessilis*), Dudhia (*Phyllanthus amarus*), Bhengraiya (*Eclipta prostrata*), and Rari (*Saccharum* sp.). Among these weeds, the first four are the most problematic. In both transplanted and direct-seeded rice, weeds are removed manually at about 30 DAS/DAT.

Fertilizer application. No fertilizer is applied basally to transplanted/direct-seeded rice. P and K are not usually applied. About 35–40 kg N ha^{-1} is applied twice (30 DAS/DAT) and at the boot stage where HYVs are grown. For direct-seeded rice with traditional varieties, only 30–35 kg N ha^{-1} is applied once at the boot stage.

Irrigation. Only the transplanted crop is given life-saving irrigation by tubewells. Direct-seeded rice is entirely rainfed. In the event of drought, transplanted puddled rice suffers more because of the development of wider and deeper cracks than in direct-seeded rice.

Insect pests and diseases. No significant damage by insect pests occurs. Severe incidence of brown spot can take place under moisture stress, and variety Lal Sita is susceptible to this disease under stress conditions.

Harvesting and yield. The crop is harvested in November. Yield of the transplanted crop under irrigated conditions is 3.5 to 4.0 t ha^{-1}, whereas traditional variety Hathihulan under direct-seeded rainfed conditions yields 2.5 to 3.0 t ha^{-1} in a normal year and 1.5 to 2.0 t ha^{-1} under drought situations.

Boro rice

Varieties. In the past, boro rice was cultivated in small pockets in river beds of Ganga, Gandak, and Kosi with traditional tall varieties having weak stems, coarse grain, and poor yield. Boro rice area has now extended to lowlands, fringes of *chaur* land, and other waterlogged areas in north Bihar. Farmers grow early-duration (Pusa 2-21, Saket-4, and Pusa-33) and medium-duration (Sita, Sujata, Jaya, and IR8) rice varieties. In Katihar District, even long-duration variety Mahsuri is grown. Variety Gautam, released recently by RAU, and possessing cold tolerance, has occupied a large area. Recently released short-duration varieties Dhanlakshmi and Richcharia, maturing 20 d earlier than Gautam, are also suitable for growing in the boro season, especially in areas having limited irrigation. Dhanlakshmi possesses tolerance of Zn deficiency.

Raising of nursery. Raising of a boro rice nursery is a challenging task as it is prone to cold damage. Nursery beds are prepared after adding compost and NPK fertilizer and 60–70 kg of seeds are sown in a nursery bed of 1,000 m^2 (to transplant 1 ha of land) from mid-October to mid-November. Seedlings attain sufficient height before a fall in temperature. Densely populated seedlings appear to have more cold tolerance than sparsely populated ones. To protect seedlings from cold injury, the nursery beds are irrigated frequently, dew drops adhered to leaf tips are made to fall by running a bamboo stick over the canopy of seedlings, and wood ash at weekly intervals is broadcast over leaves.

To reduce the duration in the nursery bed, some farmers have started raising seedlings by the *dapog* method. Seeds are soaked for 24 h and kept in a gunny bag for 2 d. Sprouted seeds are spread over a plastered floor or plastic sheet or even banana leaves at 3 kg m^{-2} in December. Seeds germinate slowly and seedlings become ready for transplanting within a month or so.

Tillage and stand establishment. Boro rice is generally grown in areas that are not available for sowing of rabi crops because of excess soil moisture or waterlogging. There is not much scope for preparatory tillage. One plowing (two passes) before final puddling is enough. Conventional or dapog seedlings are transplanted from mid-January to mid-February, when minimum ambient temperature is above 12 ºC.

Seedlings are transplanted at 15 × 15-cm spacing with 2–3 seedlings $hill^{-1}$. Gap filling is a must after 10–12 d as higher seedling mortality takes place. About 10–12 irrigations are required. A fertilizer dose of 120 kg N + 60 kg P_2O_5 + 30 kg K_2O ha^{-1} is recommended.

Yield. The crop raised with conventional seedlings (October-November sowing) yields 1–1.5 ha^{-1} more than that grown with dapog seedlings (5–6 t ha^{-1}). The culms of rice with dapog seedlings remain very thin, affecting yield attributes and thereby grain yield adversely.

Scope of direct seeding of rice in different ecosystems

Several experiments conducted in India and abroad have revealed that yields of transplanted and direct-seeded rice are similar if proper water management and weed control measures are adopted.

With the increase in irrigation facilities and availability of herbicides for controlling weeds, the replacement of transplanted rice by direct-seeded rice has become a possibility and has the following potential advantages:

1. Direct-seeded rice matures 7–10 d earlier than transplanted rice and vacates the land for timely sowing of a succeeding crop, which is necessary for higher yield.
2. Direct seeding is cost-effective. It can save nearly Rs. 3,000 ha^{-1} over transplanting up to the crop establishment stage. The expenses in raising seedlings, puddling, uprooting of seedlings, and transplanting are eliminated in direct seeding.
3. The younger generation in the farming community would prefer direct seeding because of less drudgery in farm operations than with transplanting.
4. Direct-seeded rice may tolerate drought better than transplanted rice. In heavy-textured soil, cracking occurs more in transplanted rice in the event of drought. During a drought period, farmers had to irrigate the transplanted rice 8 times versus 5 times in direct-seeded rice to save the crop in heavy-textured *tal*-land soils. Farmers believe that it is possible to grow a reasonably good crop of direct-seeded rice with limited irrigation when drought occurs.
5. It has been observed that at harvest the direct-seeded rice field had higher residual soil moisture than the transplanted rice field, thus ensuring satisfactory seed germination of succeeding rabi crops.
6. Most importantly, the yield of wheat after direct-seeded rice is higher than that after transplanted rice; thus, the productivity of the R-W system involving direct-seeded rice is more favorable.

Possibilities for introducing direct-seeded rice in transplanted areas

Transplanted rice is grown in the uplands of north Bihar and on medium lands and part of the rice areas in the lowlands, shallow-deepwater areas, and *dhab* and *tal* lands in the kharif season. The possibilities of introducing direct-seeded rice in place of transplanting are discussed hereunder.

Uplands of north Bihar

Previously, low-yielding maize varieties Jaunpur and Kalingpong were being grown but were subsequently replaced by high-yielding maize hybrids. Unstable yields of maize hybrids in kharif and the introduction of high-yielding maize hybrids (8–10 t ha^{-1}) in the winter season have paved the way for the introduction of transplanted rice in the uplands of north Bihar. Direct-seeded rice can be introduced easily in these uplands. The varieties should have shorter duration (100–110 d) and medium height, along with early vigor and weed-smothering ability, and good performance under limited irrigation. Sometimes, farmers transplant aged seedlings of early-maturing varieties because of a delay in rain, but yield is poor. This problem could be solved automatically by adopting direct seeding.

Medium land

This occupies about 38% of the total rice area in Bihar. There is scope to introduce direct-seeded rice in partially and fully irrigated as well as rainfed medium lands. In irrigated areas, too, farmers wait for rains for puddling to save on irrigation cost. This causes a delay in transplanting, resulting in lower grain yield. Direct seeding would help with the timely establishment of rice at lower cost. There is a need to identify suitable HYVs of medium (125–135 d) and long duration (145–155 d) for direct seeding. Long-duration HYVs MTU 7029 and Rajendra Mahsuri-1 have performed quite well after light irrigation for germination. In canal-irrigated areas, there is wide scope for direct seeding on puddled soil as well. Canal water is released from 25 May to 7 June for raising seedlings and this water can also be used for wet seeding of rice.

Lowland

Lowland rice is cultivated on 41.5% of the total rice area in Bihar. At times, rainwater accumulates on these lands because of heavy rains soon after transplanting or before seedling establishment and prolonged submergence causes seedling mortality. Direct seeding with medium-tall HYVs in June will ensure crop survival.

Shallow-deepwater

The yield of transplanted rice in this ecosystem is quite unstable because of submergence. Transplanting is done in early July after rains. In the event of heavy downpours, rainwater from catchments accumulates in the field, causing crop submergence and the development of submerged aquatic weeds. At Pusa, the performance of the direct-seeded crop (sown 25 May to 7 June) was compared with that of the July transplanted crop. The crop under the former system escaped submergence because of higher plant height and yielded 2.2 t ha^{-1}, with 70% higher yield than the transplanting method (Singh et al 1983). Topdressing of direct-seeded rice with 20 kg N ha^{-1} in early July after rain helps the plants to attain sufficient height to escape submergence. In view of these results, direct seeding in the shallow-deepwater ecosystem is a necessity.

In other flood-prone areas, such as *dhab* and *tal* land, direct seeding in transplanted areas could be adopted to counteract flood. Singh and Roy (1987) reported the feasibility of direct seeding of an early-maturing semitall rice variety from 25 May to 7 June and harvesting the crop by mid-August, before flood. One or two irrigations in May-June through “bamboo boring” would ensure a reasonably good rice yield.

Scope for direct seeding in the summer season

In summer rice areas also, direct seeding of rice in the first two weeks of March on puddled soil appears to be feasible because of better scope for water management. To save irrigation water and harvest the crop by the end of May (before the start of the hot westerly desiccating wind affecting pollination adversely), pregerminated seeds of short-duration varieties such as Richcharia and Dhanlakshmi could be sown on puddled soil in mid-February.

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Notes

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Production potential of the direct-seeded rice-wheat cropping system

S.K. Sharma and K.K. Singh

Although transplanting has been a major traditional method of rice establishment, economic factors and recent changes in rice production technology have improved the desirability of direct-seeding methods. The rising labor cost and the need to intensify rice production through double and triple cropping provided the economic incentives for a switch to direct seeding. Simultaneously, the availability of high-yielding short-duration varieties and chemical weed control methods made such a switch technically viable. As the rice production system develops, change can be expected in the methods of rice establishment. This paper reviews the direct-seeding technology for rice crop establishment, assesses the development of crop management techniques in relation to constraints posed by direct seeding, and suggests research areas for further improving the technology.

Methods of rice establishment

There are three principal methods of rice establishment: transplanting, dry seeding, and wet seeding. Transplanting involves planting rice seedlings in puddled soil. Dry seeding consists of sowing dry seeds on dry soils. Seeds can be broadcast, drilled, or dibbled. Wet seeding involves sowing pregerminated seeds in wet (saturated) puddled soil. Because the seeds are sown directly, the dry- and wet-seeding methods are jointly referred to as direct seeding. Dry seeding is practiced in rainfed lowland, upland, and flood-prone areas. Wet seeding is a common practice in irrigated areas, and it is further subdivided into aerobic wet seeding, anaerobic wet seeding, and water seeding. Seed may be broadcast or sown in rows on dry/moist/puddled soil, whereas only broadcasting is used for seeding on water. The area under direct-seeded rice has been increasing in Asia as farmers seek higher productivity and profitability to offset increasing costs and scarcity of farm labor (Balasubramanian and Hill 2000).

Direct-seeded area in Asia

Dry seeding is probably the oldest method of crop establishment and rough estimates for major rice-growing areas are given in Table 1. The direct-seeded area in Asia is about 29 million ha, which is approximately 21% of the total rice area in the region.

Table 1. Direct-seeded rice area (million ha) in various Asian countries by ecosystem.

Region/country	Rice area (million ha)	Direct-seeded area (million ha)	% area direct-seeded
South Asia			
Bangladesh	10.7	2.0	19.0
India	42.5	12.0	28.0
Pakistan	2.1	–	–
Sri Lanka	0.9	0.7	77.0
Southeast Asia			
Cambodia	1.9	0.2	10.0
China	32.1	1.5–3.0	5–9
Indonesia	11.0	2.0	18.0
Lao PDR	0.6	0.2	33.0
Malaysia	0.7	0.5	71.0
Myanmar	6.3	0.6	9.0
Philippines	3.6	1.5	42.0
Thailand	9.6	3.3	34.0
Vietnam	6.4	2.5–3.0	39–47
East Asia			
Japan	2.1	–	–
Korea	1.1	0.1	9.0
Total	131.6	27.3–29.3	21–22

Source: Pandey and Velasco (2002).

Potential advantages and disadvantages of direct seeding

Direct-seeding methods have several advantages and disadvantages over the traditional transplanting method.

Advantages

1. Direct seeding saves on labor depending on the nature of the production system and can reduce the labor requirement by as much as 50%.
2. In situations where no substantial reduction in labor requirement occurs, direct seeding can still be beneficial because the demand for labor is spread over a longer time than with transplanting, which needs to be completed within a short time.
3. Direct seeding may help to reduce the production risk where rainfall at planting time is highly variable. Direct seeding can also reduce risk by avoiding terminal drought that lowers the yield of transplanted rice, especially if the latter is established late because of delayed rainfall.
4. Irrigation water use can be reduced if direct-seeded rice can be established earlier by using premonsoon showers.

Disadvantages

1. The yield of direct-seeded rice under farmers' field conditions tends to be lower than that of transplanted rice. Poor and uneven establishment and inadequate weed control are the major reasons for its poor performance.
2. Farmers may end up using most of the labor saved by direct seeding to control weeds. In

Table 2. Grain yield (t ha^{-1}) of rice and wheat as influenced by establishment methods in rice (1993-94).

Treatment	Rice	Wheat
Direct seeding (dry line sowing)	4.91	4.72
Direct seeding (puddled + broadcasting)	4.43	4.05
Direct seeding (puddled + dibbling)	4.84	4.25
Transplanting	4.86	3.50
LSD at 5%	ns[a]	0.21

[a]ns = nonsignificant.
Source: Sharma and Gangwar (1996).

addition, the cost of chemical weed control tends to be higher than that of transplanted rice.

3. More use of chemical weed control methods in direct-seeded rice could potentially harm human health and the environment.

Effect of crop establishment methods on rice yield, economics, and energy in the rice-wheat cropping system

The results of the experiment conducted at PDCSR, Modipuram, indicated that the grain yield of rice and wheat was not affected under different crop establishment practices during the initial years of experimentation (data not shown). Mean yield of rice was 4.17 t ha^{-1} in direct-seeded puddled conditions, followed by 3.72 t ha^{-1} in transplanting and 3.62 t ha^{-1} in direct-seeded dry conditions. The maximum mean grain yield of wheat (5.38 t ha^{-1}) was obtained when rice was transplanted and the lowest (5.13 t ha^{-1}) when it was direct-seeded under puddled conditions. The total productivity of the rice-wheat system was 9.30 t ha^{-1} in direct-seeded puddled conditions, followed by 9.10 t ha^{-1} in transplanting and 8.99 t ha^{-1} in direct-seeded dry conditions. Net returns were also maximum with direct-seeded puddled rice-wheat (Rs. 14,741 ha^{-1}), followed by direct-seeded rice-wheat (Rs. 13,498 ha^{-1}), and the lowest under the puddled transplanted rice-wheat system (Rs. 12,981 ha^{-1}).

Further, it is interesting to note that, during the third year (1993-94) of experimentation, direct seeding under dry as well as puddled conditions and transplanting produced similar grain yield of rice (4.43 to 4.91 t ha^{-1}) (Table 2). However, the data have categorically shown that the yield of wheat was markedly influenced by the crop establishment practices adopted in preceding rice. Transplanting of rice resulted in significantly lower yield of succeeding wheat (3.50 t ha^{-1}) compared with the direct-seeded rice. Wheat grown after direct-seeded rice under dry conditions (aerobic) gave the maximum yield (4.72 t ha^{-1}), which was higher than that of anaerobic rice (4.05–4.25 t ha^{-1}).

Data (Table 3) revealed that the highest grain yield was recorded under transplanting of rice followed by direct seeding of sprouted rice in 1992 and 1994 and pooled except in 1993, when dry seeding of rice in plowed fields gave slightly higher yield. This was probably because direct seeding and transplanting were undertaken in clay soil and there was no effective weed management in direct-seeded rice (Dr. Dhiman, personal communication).

Data (Table 4) also indicated that crop establishment methods marginally affected rice and wheat yield in the rice-wheat system at PDCSR, Modipuram. Slightly higher, but nonsignificant,

Table 3. Grain yield of rice (t ha^{-1}) affected by different methods of crop establishment.

Treatment	Year			
	1992	1993	1994	Pooled
Direct seeding of sprouted rice seed in puddled fields	5.52	6.45	6.67	6.21
Transplanting of rice	5.78	7.54	7.03	6.78
Dry seeding of rice in plowed fields	5.05	6.53	6.15	5.91
LSD (P = 0.05)	0.51	0.33	0.53	0.46

Table 4. Grain and biological yield (t ha^{-1}) of rice and wheat as influenced by crop establishment methods.

Treatment	Grain yield			Biological yield		
	Rice	Wheat	Total	Rice	Wheat	Total
Direct-seeded	4.84	5.04	9.88	11.97	11.40	23.37
Transplanted	4.82	4.98	9.80	12.38	11.23	23.61
LSD at 5%	ns[a]	ns	–	ns	ns	–

[a]ns = nonsignificant.

Table 5. Effect of rice crop establishment methods on the productivity (t ha^{-1}) of hybrid rice, wheat, chickpea, and mustard (2002-03).

Treatment	Grain yield (t ha^{-1})			
	Rice	Wheat	Chickpea	Mustard
Direct seeding (dry bed)	7.84	5.61	1.75	2.21
Direct seeding (wet bed), drum seeder	8.11	5.50	1.69	2.18
Mechanical transplanting (puddled)	7.75	4.74	1.33	1.52
Mechanical transplanting (nonpuddled)	7.33	5.48	1.66	2.10
Manual transplanting (puddled)	7.46	4.85	1.36	1.55
LSD at 5%	0.38	0.17	0.11	0.12

Source: Gangwar and Sharma (2003).

grain and total biomass yield of rice and succeeding wheat were recorded with direct seeding vis-à-vis the transplanting treatment adopted in rice. This confirmed the earlier results that, on sandy loam clay soil, the first one or two years of experimentation did not influence the grain yield of rice or wheat but could save labor required for transplanting and result in higher economic returns.

During 2002-03, an experiment was conducted at PDCSR, Modipuram, to study the effect of crop establishment methods adopted in rice on the productivity of hybrid rice, wheat, chickpea, and mustard. Grain yield of hybrid rice (var. PHB 71) was on a par statistically in drum seeding (8.11 t ha^{-1}), direct seeding (7.84 t ha^{-1}), and mechanical transplanting (puddled) (7.75 t ha^{-1}), but significantly higher than in manual transplanting (puddled) (7.46 t ha^{-1}) and mechanical transplanting (nonpuddled) (7.33 t ha^{-1}) (Table 5). Direct seeding adopted in the previous rice crop resulted

Table 6. Comparison of yield and economic returns under different methods of rice planting.

Planting method	Mean grain yield ($t\ ha^{-1}$)		Net returns (Rs. ha^{-1})		Benefit-cost ratio	
	2000	2001	2000	2001	2000	2001
Direct seeding	4.3	3.4	13,650	8,000	2.37	1.88
Manual transplanting	5.1	4.5	16,550	11,000	2.44	2.04
Mechanical transplanting	6.5	5.1	24,750	15,500	3.25	2.55
LSD at 5%	0.8	0.7				

Source: Singh and Gangwar (2001).

Table 7. Effect of planting methods of rice on yield attributes, yield, and economics (pooled data for two years).

Planting methods	Grain yield ($t\ ha^{-1}$)	Grain productivity ($kg\ ha^{-1}\ d^{-1}$)	Net returns (Rs. ha^{-1})	Benefit-cost ratio (Rs. $ha^{-1}\ d^{-1}$)	Monetary productivity
Direct seeding	2.87	2.62	5,317	1.88	103.39
Transplanting	3.17	2.72	5,883	1.87	107.11
LSD at 5%	0.29	ns[a]	ns	ns	ns

[a]ns = nonsignificant.
Source: Singh et al (1997).

in significantly higher wheat (5.61 t ha^{-1}), chickpea (1.75 t ha^{-1}), and mustard yield (2.21 t ha^{-1}), closely followed by drum seeding and mechanical transplanting (nonpuddled), whereas the lowest yield of these crops was recorded under mechanical transplanting (puddled).

Studies on mechanizing the operations of crop establishment in the rice-wheat system produced promising results and indicated large scope for increasing yield and resource-use efficiency through mechanization (Singh and Gangwar 2001). The use of a self-propelled rice transplanter on sandy loam soil not only significantly outyielded manual transplanting and direct sowing in rice but also increased the net returns and benefit-cost ratio (Table 6). This advantage of mechanical transplanting was mainly due to the placement of seedlings at uniform depth and spacing with an equal number of seedlings per hill, which ultimately resulted in uniform crop growth and a relatively higher number of grains per panicle.

Transplanted rice produced 10.4% more grain yield than the direct-seeded crop (2.87 t ha^{-1}) (Table 7). However, physical productivity remained unaffected under both production methods because of the longer duration of the transplanted rice crop. Similarly, both planting methods did not have a differential effect on net returns, the benefit-cost ratio, and monetary productivity owing to the higher cost of cultivation of the transplanted crop.

At Pantnagar, deep tillage followed by direct sowing gave maximum rice yield (5.29 t ha^{-1}) that was on a par with all other treatments (Table 8). Although zero-tillage gave maximum wheat yield (4.30 t ha^{-1}), other treatments (Chinese drill, ridge planting, conventional and strip tillage)

Table 8. Effect of different tillage and planting techniques on rice and wheat yields and energy savings.

Treatment	Yield (t ha^{-1})	% increase in yield	Tillage energy (MJ ha^{-1})	% savings in energy
Planting technique (rice)				
Deep tillage + green manure + puddled transplanting	5.14	–	1,655	–
Conventional puddled transplanting	5.27	2.5	1,242	25.0
Deep tillage followed by line sowing	5.29	2.9	863	47.9
Green manure + puddled transplanting	5.14	–	1,242	25.0
LSD at 5%	ns			
Tillage practice (wheat)				
Conventional	4.09	2.0	1,818	3.8
Zero	4.30	7.2	450	76.2
Strip	4.01	–	496	73.2
Chinese drill	4.19	4.5	496	73.2
Ridge planting	4.11	2.5	1,890	–
LSD at 5%	0.11	–	–	–

Source: Annual report, AICRP-CS (2001-02).

Table 9. Performance parameters of different planting machines.

Parameter	ZT[a]	ST	BP	RT	CS
Effective field capacity (ha h^{-1})	0.50	0.45	0.42	0.40	0.50
Fuel consumption (L ha^{-1})	7.1	8.75	8.6	16.1	48.8
Cost of sowing (Rs. ha^{-1})	466	610	578	873	2,456
Energy requirement (MJ ha^{-1})	407	501	493	916	2,784

[a]ZT = zero-till drilling, ST = strip-till drilling, BP = bed planting, RT = rotary-till drilling, CS = conventional sowing.
Source: Singh and Sharma (2004).

gave similar yields. Zero-tillage, however, saved the maximum (76%) energy, followed by strip tillage and Chinese drills (73% each) compared with the conventional sowing.

At PDCSR, Modipuram, experiments have been in progress since 1998 to evaluate the effects of different methods of planting on the productivity and profitability of the rice-wheat cropping system. Table 9 presents the comparative performance of the zero-till drill, strip-till drill, bed planter, rotary-till drill, and conventional drill for rice and wheat sowing. Zero-till, strip-till, and rotary-till drilling and bed planting of rice and wheat saved time (74–79%), labor (74–81%), fuel (67–85%), cost (64–81%), energy (67–85%), and irrigation water (2–39%) compared with the conventional sowing (Fig. 1). Also, around 70 kg ha^{-1} year^{-1} CO_2 emissions to the environment could be reduced by the use of zero-till compared with the conventional sowing. The rotary- and strip-till drilling were economically beneficial in all aspects of the comparison, followed by bed planting, zero-till drilling, and conventional sowing. The strip-, rotary-, and zero-till drilling and bed planting provided higher rice yield (8.2%, 6.1%, 4.1%, and 4.1%) and B-C ratio (27.1%, 21.1%, 24.8%, and 8.7%) compared with the conventional sowing. The rotary-, strip-, and zero-till

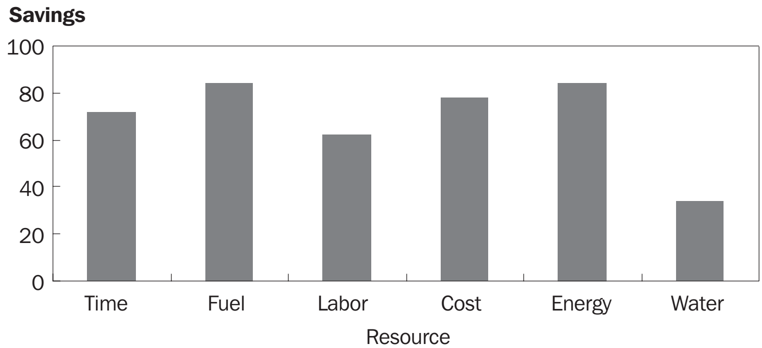

Fig. 1. Average savings of resources under zero-, strip-, and rotary-till drilling and bed planting compared with conventional sowing (water savings is mainly in bed planting). Source: Singh and Sharma (2004).

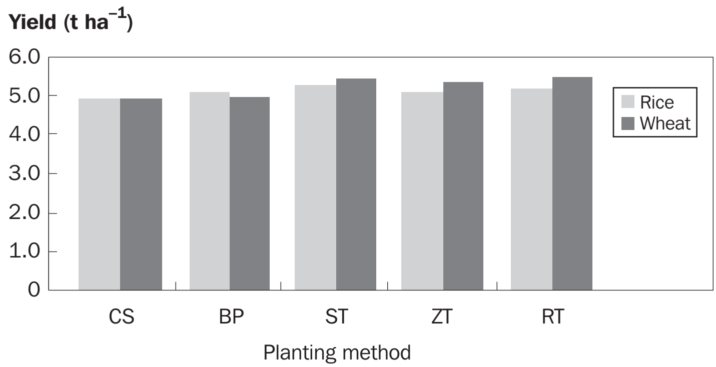

Fig 2. Effect of planting methods on rice and wheat yields (CS = conventional sowing, BP = bed planting, ST = strip-till drilling, ZT = zero-till drilling, and RT = rotary-till drilling). Source: Singh and Sharma (2004).

drilling and bed planting provided higher wheat yield (11.6%, 10.6%, 8.8%, and 2%) and B-C ratio (25%, 25%, 23.8%, and 20%) compared with conventional sowing (yield, 4.9 t ha^{-1}; B-C ratio, 2.52) (Figs. 2 and 3).

Effect of crop establishment methods on rice yield, economics, and energy in the rice-pulse/oilseed cropping system

A study was conducted at Thanjavur to find out the effect of various tillage and planting methods in the rice-pulse/oilseed system on soil structure and soil productivity. The results indicated that, during kharif, planting methods affected rice yield (Table 10). Normal puddling, green manuring, and transplanting gave a maximum rice yield (6.87 t ha^{-1}) along with the highest residual effect on black gram yield (1.07 t ha^{-1}) in summer. *Utera* cultivation yielded the maximum black gram (1.14 t ha^{-1}). Utera cultivation saved the highest (99.8%) energy and gave 22.6% higher yield than conventional sowing.

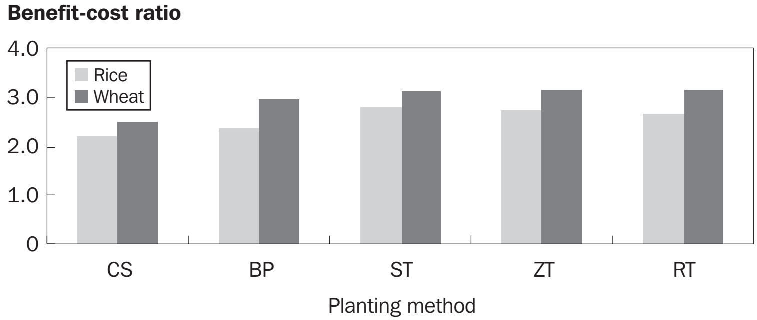

Fig. 3. Effect of planting methods on benefit-cost (BC) ratio of rice and wheat (CS = conventional sowing, BP = bed planting, ST = strip-till drilling, ZT = zero-till drilling, and RT = rotary-till drilling). Source: Singh and Sharma (2004).

Table 10. Effect of different tillage and planting techniques on the yield of rice and black gram and energy savings.

Treatment	Yield (t ha^{-1})	% increase in yield	Tillage energy (MJ ha^{-1})	% savings in energy
Planting methods (rice)				
Conventional tillage + line sowing	6.30	4.3	863	30.5
Normal puddling + transplanting	6.52	7.9	1,242	–
Normal puddling + green manure + transplanting	6.87	13.7	1,242	–
Biasi	6.04	–	866	30.3
Tillage practices (black gram)				
Utera	1.14	22.6	392	99.8
Zero	0.94	1.1	647	64.4
Conventional	0.93	–	1,818	–
Dibbling between rice stubbles	1.00	7.5	98	94.6

Source: Annual Report, AICRP-CS (2001-02).

Weed management in direct-seeded rice

At PDCSR, Modipuram, an experiment was conducted to study the effect of weed management practices on the productivity and profitability of the direct-sown rice-wheat system. The data (Table 11) showed that a stale seedbed resulted in significantly higher rice yield (4.31 t ha^{-1}) than with conventional tillage. For wheat, though the trend was the same, the increase in yield was not significant. Among weed control treatments, herbicide + one hand weeding + criss-cross sowing and herbicide + one hand weeding gave similar yield but were significantly superior to two hand weedings. Biological yields indicated that stale seedbed preparation in wheat resulted in significantly higher biomass (11.97 t ha^{-1}) than conventional tillage. For rice, though the trend was the same, the increase in yield was not significant. Among weed control treatments, herbicide + one hand weeding + criss-cross sowing and herbicide + one hand weeding gave similar yield but were significantly superior to two hand weedings.

DRRH-1 gave higher rice yield than Pusa Basmati-1 (Table 12). Hand weeding twice and herbicide application followed by one hand weeding gave similar yield of rice and wheat during

Table 11. Effect of weed management practices on the productivity (t ha^{-1}) of the direct-sown non-puddled rice-wheat system.

Treatment	Grain yield			Biological yield		
	Rice	Wheat	Total	Rice	Wheat	Total
			(t ha^{-1})			
Seedbed preparation						
Stale seedbed	4.31	4.80	9.11	11.91	11.97	23.88
Normal seedbed	3.84	4.55	8.39	10.93	11.36	22.29
LSD at 5%	0.26	ns[a]	–	ns	0.55	–
Weed control measures						
Two hand weedings	4.96	5.23	10.19	11.97	12.14	24.11
Herbicide + one hand weeding	5.32	5.92	11.24	12.60	13.36	25.96
Criss-cross sowing + one hand weeding	3.84	5.32	9.16	11.48	12.37	23.84
Criss-cross sowing + one hand weeding + herbicide	5.52	6.05	11.58	13.33	13.66	26.99
Nonweeded	0.73	0.86	1.59	7.71	6.81	14.52
LSD at 5%	0.10	0.30	–	2.85	1.31	–

[a]ns = nonsignificant.

Table 12. Rice yield, wheat yield, and BREY[a] as influenced by rice varieties and weed control.

Treatment	Grain yield (t ha^{-1})					
	1999-2000			2000-01		
	Rice	Wheat	BREY	Rice	Wheat	BREY
Varieties						
DRRH-1	6.81	5.25	10.64	7.48	3.71	9.84
Pusa Basmati-1	4.60	5.95	10.60	4.64	4.60	9.09
LSD at 5%	1.08	0.17	–	0.26	0.16	–
Weed control						
Hand weeding	5.75	5.38	10.10	5.92	3.97	8.91
Herbicide	5.62	5.50	10.14	5.97	4.25	9.30
Hand weeding + sulfur	5.82	5.54	10.32	5.99	4.06	9.15
Herbicide + sulfur	5.80	5.62	10.38	6.03	4.36	9.45
LSD at 5%	ns[b]	ns	–	ns	ns	–

[a]BREY = basmati rice equivalent yield. [b]ns = nonsignificant.
Source: Sharma and Pandey (2001).

both years. Total production was higher with the rice (DRRH-1)-wheat system than with other combinations. This was because nutrient removal was higher with DRRH-1 than with Pusa Basmati-1; therefore, wheat yield was lower after DRRH-1 than after Pusa Basmati-1. Hence, there is a need to work out the nutrient requirement of wheat succeeding hybrid rice.

Data presented in Table 13 revealed that hand weeding twice (at 15 and 30 days) gave significantly higher grain yield, and butachlor at 1.5 kg ha^{-1} was the next best effective and profitable weed control measure. Although anilofos and rice straw recorded significantly lower yields, they were better than the nonweeded control. Under sowing methods of rice, it was found that drill-

Table 13. Grain yields ($t\ ha^{-1}$) of rice as influenced by sowing and weed control methods (pooled mean of 1990, 1991, and 1992).

Sowing method	Weed control methods					
	Nonweeded	Hand weeding	Butachlor	Anilofos	Rice straw	Mean
Drilling	1.11	2.90	2.50	1.96	1.77	2.05
Raher	0.98	3.04	2.30	2.07	1.83	2.04
Dibbling	1.17	2.90	2.59	2.08	1.66	2.08
Broadcast	0.91	2.63	2.24	1.73	1.82	1.87
Mean	1.04	2.87	2.41	1.96	1.77	

LSD at 5%: weed control methods = 0.17, sowing methods = 0.15, interaction = 0.40.
Source: Mahalle (1996).

Table 14. Growth and yield of rice as influenced by agronomic practices.

Direct-seeding practice	Panicles m^{-2}	Panicle wt. (g)	Grain yield ($t\ ha^{-1}$)	Benefit-cost ratio
Sprouted seeds without NPK	298	1.99	2.54	1.81
Sprouted seeds with NPK (40:20:20 $kg\ ha^{-1}$)	296	2.05	2.85	1.81
Soaked seeds without NPK	307	1.96	2.71	1.94
Soaked seeds with NPK (40:20:20 $kg\ ha^{-1}$)	316	2.07	3.08	1.96
Soaked seeds with NPK, 50% extra plant population	299	2.03	2.71	1.62

Source: Saikia et al (1992).

ing, dibbling, and *raher* methods were on a par for grain yield and were significantly superior to the broadcast method. The crop sown by the *raher* method with hand weeding twice recorded the maximum yield (3.04 $t\ ha^{-1}$) and the crop sown by either drilling or dibbling and controlling weeds by either hand weeding or butachlor yielded statistically equal. The *raher* method and butachlor treatment, however, yielded significantly less than the hand-weeded method. Drilling, *raher*, and the broadcast method under rice straw and anilofos showed equal performance but were significantly inferior to dibbling with butachlor.

Soaked (nonsprouted) seeds gave higher grain yield than sprouted seeds both with and without fertilizer. Soaked/sprouted seeds with fertilizer performed better than the treatment without fertilizer (Table 14).

Water requirement in direct-seeded rice

Water savings (39%) in direct seeding (bed planting) compared with the conventional method of rice sowing were recorded at PDCSR, Modipuram (Fig. 1). The study on the effect of rice crop establishment methods on water requirement during 2002 to 2004 revealed that there was no difference in the water requirement of direct-seeded nonpuddled line-sown and puddled transplanted rice (Fig. 4).

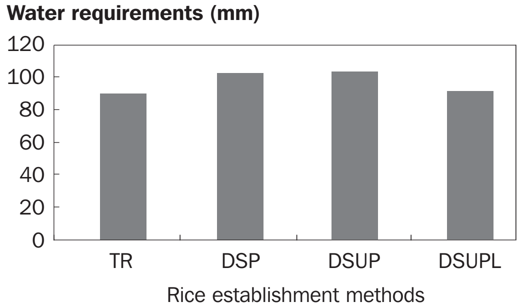

Fig. 4. Effect of crop establishment methods on water requirement of rice (TR = transplanted, DSP = direct-seeded puddled, DSUP = direct-seeded nonpuddled, DSUPL = direct-seeded nonpuddled line-sown), CD at 5% = 10.63. Source: Mishra and Sharma (2004).

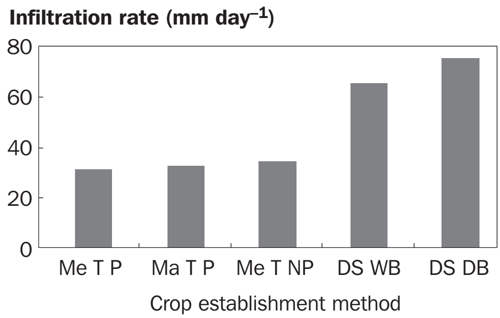

Fig. 5. Effect of rice crop establishment methods on infiltration rate (Me T P = mechanical transplanting puddled, Ma T P = manual transplanting puddled, Me T NP = mechanical transplanting nonpuddled, DS WB = drum-seeded wet bed, DS DB = direct-seeded dry bed). Source: Mishra and Sharma (2004).

The effect of rice crop establishment methods on infiltration rate was recorded at PDCSR, Modipuram, during 2004. The infiltration rates of the three transplanting methods (irrespective of puddling) were almost the same (31–34 mm d^{-1}). The infiltration rate of direct-seeded plots in a dry bed (75 mm d^{-1}) was higher than in drum-seeded plots in a wet bed (65 mm d^{-1}) (Fig. 5).

Research areas for further improving direct-seeding technology

Direct seeding offers advantages such as faster and easier planting; reduced labor, fuel, energy, and drudgery; earlier crop maturity by 7–10 d; more efficient water use and higher tolerance of water deficit; fewer methane emissions; and often higher profit in areas with an assured water supply. Although labor and its associated costs may be reduced for crop establishment, other technologies are essential to overcome constraints imposed by direct seeding. For example, we should enhance the interaction of crop stand establishment, water management, and weed control in relation to crop lodging in both dry- and wet-seeded rice. Technology for land preparation, precision leveling, and prevention of crop lodging must be improved in wet direct-seeded rice. Similarly, management practices and control strategies are currently lacking for several pests (rats, snails, birds, etc.) that damage surface-sown seeds and for problem weeds that compete with rice seedlings. Greater understanding is required of the effect of seed rate or tiller density on weed pressure, pest damage, grain yield, grain quality, harvest index, and crop lodging at maturity to develop management strategies for direct-sown rice in the tropics. Higher resistance to lodging is essential in rice varieties selected for intensive direct seeding to achieve high yields. Furthermore, varieties must be improved or hybrids could be used for early seedling vigor, synchronous tillering, weed competitiveness, tolerance of low oxygen level of submergence, and tolerance of drought. We must find practical solutions to alleviate these constraints and to ensure optimum conditions for seeding. Only then, direct seeding may become an attractive and sustainable alternative to traditional transplanting of rice.

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Long-term sustainability of the rice-wheat cropping system in the Indo-Gangetic Plains

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Sustainability of the rice-wheat cropping system (RWCS) is very important as hundreds of millions of rural and urban poor in South Asia depend on it for their employment, income, and livelihood. Nearly 85% of the RWCS in the region is located in the Indo-Gangetic Plains (IGP). Though there are several definitions and approaches to measuring sustainability, most of them consider it as the capacity of a system to maintain output at a level approximately equal to or greater than its historical average. The area under the RWCS in the IGP appears to have stabilized, and future increases in the total production of rice and wheat can be achieved only by enhancing their productivity. Several researchers in the past have expressed concern over some factors that are either affecting or threatening to affect the sustainability of the RWCS. These constraints include climate change such as decreasing solar radiation and increasing minimum temperatures and delayed onset of monsoon, shortage of water and depletion of groundwater resources, shortage of labor, puddling in rice and extensive tillage in wheat, a decline in soil organic matter, nutrient depletion and imbalances and emerging multiple nutrient deficiencies, burning of rice straw after harvest, increasing incidence of *Phalaris minor*, and other pests and diseases. Different researchers evaluated possible strategies to overcome the constraints. Direct-seeded rice, minimum or no tillage in wheat, the introduction of improved seed drills in wheat, incorporation of legumes, and integrated nutrient, weed, pest, and disease management strategies are some of the practices recommended for increasing the system's productivity. Further research on the impact of existing and improved farming practices on system sustainability is recommended. It is also suggested that sustainability of the system be monitored by conducting regular on-farm studies.

The rice-wheat cropping system (RWCS) is one of the most important agricultural production systems in the world owing to the large extent of area it occupies and the vast population it feeds. The system spans four countries in the Indo-Gangetic Plains (IGP) region, Bangladesh, India, Nepal, and Pakistan, and occupies about 13.5 million ha. It accounts for about one-third of the area of both rice and wheat grown in South Asia, and it produces staple grains for more than 1 billion people, or about 20% of the world's population. There are both favorable irrigated areas with high productivity in the western parts and not so favorable rainfed areas with low productivity in the eastern parts (Ladha et al 2000). Sources of irrigation include both river canals and tubewells. In the northwest parts of the IGP, the RWCS is highly mechanized, input-intensive, and dependent on conjunctive use of surface water and groundwater. In contrast, in the eastern IGP, it is less mechanized, low-input based, and prone to problems of poor drainage and rainwater management (Velayutham et al 1999).

The soils are generally fertile and are loamy and silty clay loamy in texture with moderate water and nutrient retention capacities. Farmers in the region have been cultivating the two crops, one followed by the other, for several decades. In this system, rice is grown in the *kharif* (wet) season, followed by wheat in the *rabi* (dry) season. A rice nursery is sown in May, transplanted in June, and harvested in October. This is followed by wheat in the cooler and comparatively dry winter months (November to March).

The adoption of Green Revolution technologies in the 1960s and 1970s increased yield significantly. Thereafter, the growth rates have declined, giving rise to concern that future production increases may not keep pace with the population that will continue to expand. At the same time, the area under the RWCS decreased in per capita terms from 1,200 m^2 in 1961 to 700 m^2 now (Ladha et al 2003a). A yield increase is the only option now, as the areas are already intensively cropped, to cope with the growing demand for food grains (FAO 1999). However, researchers started questioning the sustainability of the rice-wheat system in the light of slowing yield growth and degradation of the resource base (Hobbs and Morris 1996, Ladha et al 2003c). These concerns were mainly expressed with reference to the high-input intensive areas of the northwest IGP.

Defining sustainability

The term “sustainability in agriculture” was defined by several researchers and organizations. These definitions (FAO Council 1988, Lynam and Herdt 1989, Ehui and Spencer 1990, Herdt and Lynam 1992) considered factors such as production, productivity, input and output, profitability, and environmental safety. According to the FAO Council (1988), “sustainable development is the management and conservation of the natural resource base, and the orientation of institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future. Such sustainable development (in agriculture, forestry, and fisheries sectors) conserves land, water, plant, and animal genetic resources, is environmentally nondegrading, technically appropriate, economically viable, and socially acceptable.” This definition may have some variations in different countries. A common denominator should, however, be not to compromise increased productivity as the demand for food continues to increase with the growing number of people.

A definition of sustainability that could be measured in quantifiable terms is given by Lynam and Herdt (1989). They defined sustainability as the “capacity of a system to maintain output at a level approximately equal to or greater than its historical average” and “technology contributes to sustainability if it increases the slope of the trend line.” This approach suggested total factor productivity (TFP) as a measure of sustainability, and a system having a nonpositive trend in TFP was considered sustainable. It calculates the ratio of the total value of all outputs to the total value of all inputs for a given production system in monetary terms. A modified version that included soil nutrients and land degradation in the valuation was presented by Ehui and Spencer (1990). The TFP approach has been criticized because it does not internalize external costs, such as environmental effects (Hailu and Runge-Metzger 1993). Positive TFP growth by itself does not necessarily indicate sustainability of the system. As TFP does not consider the costs of environmental degradation, positive TFP growth is possible although there may be deterioration of soil and water

Table 1. Area (million ha) under rice and wheat in rice-wheat regions of the Indo-Gangetic Plains.

Country/state	Area (million ha)				
	1972	1975	1985	1995	2002
Rice					
Bangladesh	9.6	10.3	10.4	10.0	10.8
Nepal	1.1	1.3	1.4	1.5	1.6
Pakistan	1.5	1.7	1.9	2.2	2.2
Uttar Pradesh	4.6	4.5	5.5	5.6	5.9
Bihar	5.1	5.2	5.1	4.8	5.1
West Bengal	5.0	5.4	5.2	5.9	6.1
Punjab	0.4	0.6	1.6	2.2	2.5
Haryana	0.3	0.3	0.6	0.8	1.0
Wheat					
Bangladesh	0.1	0.1	0.7	0.6	0.7
Nepal	0.2	0.3	0.5	0.6	0.7
Pakistan	5.8	5.8	7.3	8.2	8.1
Uttar Pradesh	6.0	6.2	8.4	9.0	9.1
Bihar	1.7	1.5	1.9	2.1	2.1
West Bengal	0.4	0.4	0.3	0.3	0.4
Punjab	2.3	2.3	3.1	3.3	3.4
Haryana	1.2	1.2	1.7	2.0	1.3

Sources: www.fao.org for data on Bangladesh, Nepal, and Pakistan; Kumar et al (1999) for data on Indian states for 1972-95; and http://agricoop.nic.in/statistics2003/chap4a.htm for data on Indian states for 2002.

quality that could potentially endanger the system sustainability. 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. Herdt and Lynam (1992) tried to overcome this shortcoming by proposing total social factor productivity (TSFP) as a more advanced approach than TFP. TSFP included the environmental costs of production, but the question remains about how to value environmental costs appropriately and where to draw the boundary of internalization. In this approach to sustainability, the output includes not only grain and straw but also any gains made in soil fertility and the environment. Similarly, the input includes not only the paid costs of inputs and labor but also any losses to soil nutrient status and environment. In other words, it is important to harvest the same or more grain from the land without any degradation in land productivity, that is, the continuing ability of the system to sustain the output levels. Later, Whitaker and Lalitha (1993) used intertemporal factor productivity to measure the sustainability of a crop or farming system.

Status of the RWCS and its sustainability in the IGP

Precise estimates of the extent of area under the RWCS in the IGP in the recent past are not available. Some estimates were made using the data on area under rice and wheat and deducting from it the area under other systems. The area, production, and productivity of rice and wheat in RWCS regions are given in Tables 1–3. Area and production expanded in all four countries (India, Pakistan, Bangladesh, and Nepal) during 1972-2002. In India, the areas of rice and wheat expanded across

Table 2. Production (million Mg) of rice and wheat in rice-wheat regions of the Indo-Gangetic Plains.

Country/state	Production (million Mg)				
	1972	1975	1985	1995	2002
Rice					
Bangladesh	15.1	19.1	22.6	26.4	37.6
Nepal	2.0	2.6	2.8	3.6	4.1
Pakistan	3.5	3.9	4.4	6.0	6.7
Uttar Pradesh	3.6	3.9	7.4	10.3	12.5
Bihar	4.6	4.5	5.5	6.4	6.9
West Bengal	6.1	6.4	8.0	12.2	15.3
Punjab	0.9	1.3	5.0	7.4	8.8
Haryana	0.5	0.5	1.4	2.1	2.7
Wheat					
Bangladesh	0.1	0.1	1.5	1.3	1.6
Nepal	0.2	0.3	0.5	0.9	1.3
Pakistan	6.9	7.7	11.7	17.0	18.2
Uttar Pradesh	7.6	7.2	11.2	21.9	25.0
Bihar	2.3	2.0	3.0	4.3	4.4
West Bengal	0.8	0.9	0.8	0.7	1.0
Punjab	5.4	5.4	9.7	13.2	15.5
Haryana	2.3	2.1	4.7	7.3	9.4

Sources: www.fao.org for data on Bangladesh, Nepal, and Pakistan; Kumar et al (1999) for data on Indian states for 1972-95; and http://agricoop.nic.in/statistics2003/chap4a.htm for data on Indian states for 2002.

the IGP in the states having the RWCS, indicating increased preference of the system by farmers. However, as the figures indicate, the area under rice and wheat has stabilized and expansion in the future is less likely. As mentioned earlier, Ladha et al (2003a) reported a decline in the per capita land area of the rice-wheat system from 1,200 m^2 in 1961 to 700 m^2 now. This decrease is likely to continue as population numbers continue to rise and competition from other crops increases.

The total production of both rice and wheat also increased with time (Table 2), and area expansion could be the major source of this growth. The growth in production, however, slowed down in the later years. For productivity, the overall trends in the productivity of rice and wheat in different parts of the IGP show an increase (Table 3). Though the growth of yield has slowed, there was no evidence of an absolute decline in farmers' fields (Byerlee et al 2003). Some reports also show evidence of stagnation or decline in productivity (Woodhead et al 1994, Duxbury et al 2000, Ladha et al 2003b, Pathak et al 2003). These reports suggested declining soil organic matter content and the emergence of new weeds, pests, and diseases as the possible reasons for a decline in yield.

Studies were conducted on TFP in the RWCS by Ali and Byerlee (2000) in Pakistan and Kumar et al (1999) and Murgai (2000) in India. Ali and Byerlee summarized TFP growth rates in different cropping systems of the Punjab in Pakistan during 1966-94. They suggested a negative growth rate in TFP in the earlier years of the Green Revolution (1966-74), and a relatively positive growth rate during 1985-94. However, a positive trend does not necessarily imply a sustainable

Table 3. Yield (Mg ha^{-1}) of rice and wheat in rice-wheat regions of the Indo-Gangetic Plains.

Country/state	Yield (Mg ha^{-1})				
	1972	1975	1985	1995	2002
Rice					
Bangladesh	1.6	1.9	2.2	2.7	3.5
Nepal	1.8	2.1	2.0	2.4	2.7
Pakistan	2.4	2.3	2.3	2.8	3.0
Uttar Pradesh	0.8	0.9	1.4	1.8	2.1
Bihar	0.9	0.9	1.1	1.3	1.5
West Bengal	1.2	1.2	1.5	2.1	2.5
Punjab	2.0	2.3	3.11	3.3	3.5
Haryana	1.7	1.8	2.6	2.6	2.7
Wheat					
Bangladesh	0.9	0.9	2.2	1.9	2.2
Nepal	0.9	1.1	1.2	1.4	1.9
Pakistan	1.2	1.3	1.6	2.1	2.3
Uttar Pradesh	1.3	1.2	1.3	2.4	2.8
Bihar	1.3	1.3	1.6	2.1	2.1
West Bengal	2.2	2.0	2.5	2.3	2.2
Punjab	2.3	2.3	3.1	4.0	4.6
Haryana	2.0	1.8	2.7	3.7	4.1

Sources: www.fao.org for data on Bangladesh, Nepal, and Pakistan; Kumar et al (1999) for data on Indian states for 1972-95; and http://agricoop.nic.in/statistics2003/chap4a.htm for data on Indian states for 2002.

system in the long term, especially if it has been achieved at the cost of resource degradation. Kumar et al (1999) attempted to measure sustainability of the RWCS in India. Their results suggested a growth in TFP in Punjab and Haryana from 1976 to 1985 to 1992 (Table 4). However, in the case of Uttar Pradesh and overall IGP, they estimated a decline in TFP from 1985 to 1992. They calculated the growth rates in input and output indices and TFP. The TFP growth rates were higher during 1976-85 than during 1985-92. The annual growth rate of TFP in Punjab declined from 3.2% during 1976-85 to 0.8% during 1985-92, and in Haryana from a positive 2.4% to a negative 0.1% (though nonsignificant) during the corresponding periods. The growth rates of TFP during 1985-92 were reported to be negative for Uttar Pradesh and the overall IGP region also, though nonsignificant for the latter. Studies of Murgai (2000) used district-level data from Punjab and Haryana, which also reported a TFP growth rate of more than 1.5% in eight out of nine districts of the two states during 1985-93.

Pathak et al (2003) analyzed the trends of climatic potential and on-farm yields of rice and wheat in the IGP and suggested possible adverse changes in weather parameters and a consequent decline in potential yields. In view of these trends and also the emerging problems with the rice-wheat system, achieving the required growth rate of 2.5% to meet the food grain demands of the population in the region in the coming years appears to be a daunting task.

A pictorial representation of the sustainability dimensions of the RWCS in the IGP is depicted in Figure 1 (RWC-CIMMYT 2003). Factors such as delayed sowing of rice and wheat,

Table 4. Trends in indices of total factor productivity of the RWCS in the Indo-Gangetic Plains in India.

State	Index[a] (%)			Annual growth rate (%)		
	1976	1985	1992	1976-85	1985-92	1976-92
Punjab						
Input index	47.3	137.3	172.1	10.9	3.3	7.2
Output index	35.8	134.5	177.6	14.0	4.1	9.1
TFP	75.8	97.9	103.1	3.2	0.8	1.9
Haryana						
Input index	62.9	114.2	156.1	5.3	5.2	4.2
Output index	53.0	118.4	162.2	7.7	5.1	5.6
TFP	84.2	103.7	103.9	2.4	–0.1 ns	1.4
Utter Pradesh						
Input index	88.5	94.2	113.9	0.9	3.5	1.4
Output index	87.9	121.0	136.8	3.1	2.3	2.9
TFP	99.3	128.4	120.1	2.2	–1.2	1.6
Indo-Gangetic Plains						
Input index	78.3	104.6	127.8	3.2	3.5	3.4
Output index	69.9	126.0	151.8	6.1	3.1	4.9
TFP	89.3	120.4	118.8	2.9	–0.4ns	1.5

[a]Index numbers are the average figures for triennium ending 1976, 1985, and 1992.
ns = statistically not significant.
Source: Kumar et al (1999).

groundwater depletion, soil degradation, and weed resistance are shown to be leading to stagnation of yield below the potential level. Some constraints affecting the productivity of the RWCS and strategies suggested by different researchers to overcome them appear in Table 5.

One strategy that was often recommended by the researchers is to promote direct-seeded rice (DSR) as an alternative to transplanted rice (TPR), especially in areas experiencing a shortage and high costs of water and labor. However, some problems with DSR should be addressed so as to make it a readily acceptable alternative to the conventional puddled TPR. The major strategies to make DSR a promising option follow:

- Identify and demarcate areas suitable for dry and wet seeding and promote the adoption of the same accordingly.
- Varieties specifically suitable for DSR, if not available, need to be developed.
- Time and method of seeding need to be optimized.
- Tillage systems suitable for DSR should be standardized.
- Enhanced weed infestation is a constraint for the adoption of DSR, and efficient and economically viable weed management options need to be developed and provided to farmers.
- Seeding rates should be evaluated for DSR under varying conditions of soils and resource availability.

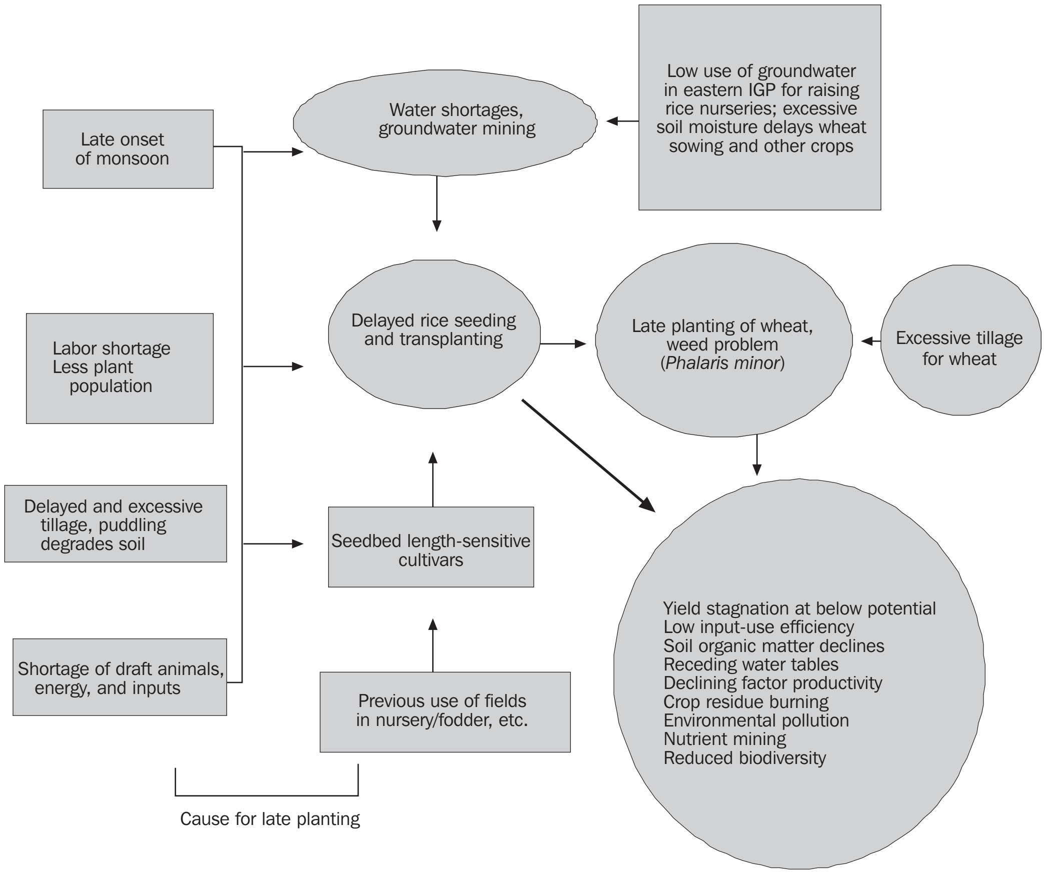

Fig. 1. Sustainability dimensions of the rice-wheat system in the Indo-Gangetic Plains (RWC-CIMMYT 2003).

Sustainability issues for consideration

Measuring sustainability

Quantifying the sustainability of the RWCS based on well-authenticated data is important to judge the actual status of the system and the impact of the farming practices with reference to the sustainability of the system. Methods for measuring sustainability should be able to measure not only the economic factors but also the environmental costs and benefits while working out the productivity. Such methods should be developed and validated. Since studies on sustainability involve measurement of a number of factors and parameters that vary substantially under farmers' field conditions, it is important to develop and use proper statistical techniques to collect the data and subject them to suitable analysis to make the exercise more robust.

Spatial variability of sustainability in the IGP

It is also important to estimate the sustainability of the RWCS in different environments across the IGP to understand the spatial variability and the reasons for it. There are high-input intensive areas

Table 5. Some constraints affecting the productivity of the rice-wheat cropping system and the strategies to overcome them.

S. no.	Constraints limiting the productivity of sustainability		Strategies to overcome the constraints		
	Factors	Consequences	Practices	Rationale	References
1	Climate changes such as decreasing solar radiation and increasing minimum temperatures (Aggarwal et al 2000, Pathak et al 2002)	Decreased photosynthesis, increased respiration, shortened vegetative and grain-filling periods	Stop burning crop residue	Reduced emission of greenhouse gases	Miura and Kanno (1997), Kukla and Karl (1993)
	Late onset of monsoon (Gupta et al 2003)	Delayed sowing of rice nursery, delayed harvest of rice, reduced turnover period, delayed wheat sowing, reduced yields of rice and wheat	Promote direct-seeded rice	Direct seeding advances crop establishment by 40–55 days and harvesting of rice by 15–30 days compared with transplanted rice	Morris (1982), Pandey and Valesco (1999), Hobbs and Gupta (2000), Hobbs et al (2001), Gupta et al (2002)
			Promote no-till wheat	Beneficial effects on soil structure and reduction in the likelihood of delayed sowings, time required for tillage operations in wheat is saved	Hobbs and Gupta (2003)
2	Shortage of water, depletion of groundwater resources in IGP (Harrington et al 1993, Gill 1994)	Lack of enough water for puddling, high costs of water, reduced yield and net income	Laser leveling of land	Improved water management, crop stand, and productivity	Rickman et al (1998), Gupta and Gill (2003)
			Shift from transplanted rice to direct seeding	Direct-seeded rice is more water-efficient	Guerra et al (1998)
			Raised-bed system for wheat	30–35% water savings in wheat grown on raised bed	Hobbs (2003), Connor et al (2003)

Continued on next page

Table 5 continued.

S. no.	Constraints limiting the productivity of sustainability		Strategies to overcome the constraints		
	Factors	Consequences	Practices	Rationale	References
3	Shortage of labor, especially when needed most for operations such as transplanting (Janaiah and Hossain 2003)	Increased costs of labor and reduced profits	Promote direct seeding of rice	Reduced dependence and costs of labor for transplanting	Pandey and Valesco (1999)
4	Puddling in transplanted rice (Sharma et al 2003)	Breaks soil structure, results in poor aeration and unfavorable soil conditions for wheat	Reduced tillage in rice	Soil structure is not destroyed, and soil productivity is retained	Sharma et al (2003)
			Promote direct seeding of rice	Dry direct seeding doesn't require any puddling	Balasubramanian et al (2003)
			Direct drilling of wheat (without tillage)	No or minimum tillage results in reduced turnaround time	Aslam et al (1993), Mehla et al (2000)
5	Decline in soil organic matter (SOM) (Bronson et al 1998, Timsina and Connor 2001, Ladha et al 2003a)	Reduced soil fertility and system productivity	Avoid burning of rice straw, retain it as surface mulch or incorporate it	Rice straw residues help build up SOM	Grace et al (2003), Samra et al (2003)
				Mulching reduces weed infestation and also improves water retention	
			Introduce a leguminous crop such as *Sesbania* prerice and postrice or a postrice crop season	*Sesbania* incorporation helps build up SOM	Ladha and Garrity (1994), Haqqani et al (2000), Lauren et al (2001)
6	Nutrient depletion and imbalances (Duxbury et al 2000, Bhandari et al 2002, Regmi et al 2002, Pathak et al 2003)	Emerging problem of deficiencies of secondary micronutrients such as S and Zn, B, and other micro-nutrients	Deep placement of N fertilizer	Reduced N losses and increased N-use efficiency with deep placement	Mohanty et al (1999), Ladha et al (2000)
	Emergence of multiple nutrient deficiencies (Abrol et al 2000, Byerlee et al 2003, Ladha et al 2003a, Pathak et al 2002)	Reduced nutrient-use efficiencies	N applications based on leaf color chart (LCC); P and K management based on omissions plot technique	Improved use efficiencies of nutrients and increased yields	Balasubramanian et al (2003)
		Increased costs of production and reduced income		Reduced losses, timely availability of nutrients, and improved physiological and agronomic-use efficiencies	Balasubramanian et al (2003)

Continued on next page

Table 5 continued.

S. no.	Constraints limiting the productivity of sustainability		Strategies to overcome the constraints		
	Factors	Consequences	Practices	Rationale	References
7	Burning of rice straw after harvest (Sharma and Mishra 2001, Abrol et al 2000, Timsina and Connor 2001)	Air pollution and substantial loss of nutrients and potential SOM	Promote improved seed drills	Wheat sowing could be done even in the presence of loose residues without tillage	Gupta and Rickman (2002)
8	Excessive tillage in wheat (Harrington et al 1993, Ortiz-Monasterio et al 1994, Hobbs and Gupta 2003)	Late planting of wheat and consequently reduced yields	Promote minimum or zero-tillage in wheat	Time required for wheat tillage is saved	Malik (1996), Hobbs et al (1997), Abrol et al (2000), Gupta et al (2000), Mehla et al (2000), Tullberg et al (2001), Hobbs and Mehla (2003)
9	Increasing populations of *Phalaris minor* (Sinha et al 1998) and its resistance to isoproturon (Malik et al 1998)	Increased costs of weed management and reduced net income to farmers	Avoid burning of rice straw residue	Burning of rice straw enhances the survival of *Phalaris minor* by reducing the efficacy of isoproturon	Malik et al (1998)
			Practice integrated weed management by judicious use of herbicide	Avoids development of resistance of *Phalaris minor* to the new herbicide molecules	Malik et al (1998)
10	Increased incidence of pests and diseases (Byerlee and Siddiq 1994, Aggarwal et al 2000)	Increased costs of pest management, reduced net income	Adopt integrated pest and disease management practices	Avoids pest resistance and resurgence; provides efficient management of pests in the long term	Sehgal et al (2001)

and low-input areas with unfavorable environments, and the sustainability of these systems should be measured independently.

Studies on system productivity rather than on individual crops

Sustainability of the RWCS should be studied on a system basis rather than on an individual crop basis. A practice suitable for rice cultivation may or may not lead to favorable conditions for the succeeding wheat crop and vice versa. Hence, it is important to understand how a given technology affects not just the yield of rice or wheat but that of both. Similarly, attempts to find suitable alternative crops should evaluate the sustainability of one cropping system with that of the other, and not just the economic returns of one crop against the other. There have been extensive studies on the rice-wheat system, but the data are mostly evaluated and presented for rice and wheat separately. It is important to study and present their productivity and profitability on a system basis.

Sustainability studies in farmers' fields

Evaluation of system sustainability based on data from controlled research station studies will not truly depict the status of the system at the farmer level. A true picture of a system's profitability to farmers and its sustainability could be obtained from the studies done at the farmer level only. Attempts should be made to measure the sustainability of the RWCS by regular on-farm monitoring to make a correct assessment of the existing and improved farming practices.

Conclusions

Economic returns and ecosystem health are important indicators of system sustainability. It is therefore essential to develop and promote technologies that could enhance the efficiencies of paid inputs such as fertilizer, tillage, water, and labor on the one hand and to preserve soil and ecosystem health on the other to make the RWCS more remunerative to farmers and sustainable in the long term. DSR could be considered as a viable alternative to puddled transplanted rice in areas that are already experiencing a shortage of water and labor. At present, no varieties are specifically bred for DSR in the IGP, and efforts to breed varieties that could perform well under DSR conditions should be made. It is important to evaluate the sustainability of the technologies in the RWCS on a system basis rather than on an individual crop basis. There is also a need to develop tools to measure the environmental costs and benefits of technologies so as to quantify the impacts of such technologies on system sustainability accurately. Though difficult, it is more relevant to measure sustainability of a system at the farmer level by conducting regular on-farm studies.

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Changes in rice-wheat production technologies and how rice-wheat became a success story: lessons from zero-tillage wheat

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The large-scale adoption of zero-till wheat by farmers under the rice-wheat system in the Indo-Gangetic Plains (IGP) is contributing to savings in cost, fuel, time, energy, and water. Zero-till sowing of wheat saves Indian Rs. 2,500–3,000 ha^{-1} on land preparation, about 10% water, and 60–75 L of diesel ha^{-1} compared with transplanting, and advances sowing time by 1–3 weeks in different parts of the IGP. It also reduces the density of *Phalaris minor* by 30–40% and provides an option for partial residue burning, thus reducing air pollution, and increases the organic matter status of soil. The residue left standing in zero-till provides a friendly habitat for beneficial insects, including spiders. It increases fertilizer-use efficiency and reduces wear and tear on tractors and other farm implements.

Taking lessons from zero-till wheat, the Rice-Wheat Consortium (RWC) in partnership with national, regional, and international programs has been trying to promote various resource-conserving technologies such as laser leveling, the furrow-irrigated raised-bed system in both rice and wheat, surface seeding of wheat, direct seeding of rice (DSR), transplanting of rice in zero-till/nonpuddled conditions, intercropping of *Sesbania* in DSR, boro rice, the leaf color chart, and the use of new-generation machines for handling crop residues. Bed planting, which is a water-saving technology, does not save on land preparation costs or time when beds are formed for the first time. But, using the beds permanently for subsequent crops will prove beneficial. Moreover, this system of cultivation provides an opportunity for diversification since oilseeds and pulses gave 10–25% higher yields when grown on beds. In addition, intercropping such as sugarcane in furrows and wheat on beds may prove more beneficial and sustainable. The use of new-generation machines for handling crop residues avoids residue burning, thereby improving environmental quality and reducing greenhouse gas emissions. These technologies are aimed at maximizing returns per unit of input with efficient use as well as conservation of natural resources. Work is being carried out directly in farmers' fields to reduce the gap between development and adoption of the new resource-conservation technologies. This paper discusses new production technologies for both rice and wheat crops.

Rice and wheat together contribute more than 70% to the total cereal production in India. The estimated area of the rice-wheat system in India, Pakistan, Bangladesh, and Nepal is about 10.0, 2.2, 0.8, and 0.5 million ha, respectively (Ladha et al 2000). At present, the food situation is satisfactory, but increasing production to meet the needs of the ever-growing population in South Asia is full of uncertainties. With the increase in population, more and more land will be required for domestic and industrial purposes. In addition, urbanization will also lead to a further decline in area for agricultural use.

Earlier, agriculture focused on achieving food security through increased coverage under high-yielding varieties, expansion of irrigation, and increased use of external inputs. This enabled rice-wheat to emerge as a major cropping system in the IGP, leading to the Green Revolution. But these factors are bound to have less influence on yield growth in the future, as the response to these factors is lower since we have almost reached a plateau in productivity. Groundwater pollution and decreasing soil fertility and organic matter status of the soils are other factors of concern. This evidence indicates that the rice-wheat system has weakened the natural resource base. If we continue to exploit natural resources, productivity and sustainability are bound to suffer. Therefore, to meet the aim of sustainable yields over the years, we need to avoid further degradation of natural resources. Moreover, in the face of the World Trade Organization (WTO) regime, we must produce at a lower cost to be competitive in the international market, with India already being a surplus nation in food-grain production. To meet these needs, the agricultural system must develop cost-effective technologies suitable for harnessing the untapped potential, especially in the northeastern parts of the IGP.

Resource-conservation technologies in wheat

Zero-tillage

Zero-tillage (ZT) is a resource-conservation technology in which wheat is directly seeded into the undisturbed soil after rice harvesting using a specially designed machine. In this technology, seed and fertilizer are placed into the narrow slits created by the inverted-T-type furrow openers of the ZT ferti-seed drill. This technique was first adopted in the high-yielding, more mechanized areas of northwestern India and Pakistan, where a lot of money was being invested in field preparation. This technology provided an opportunity to reduce the cost of cultivation by Rs. 2,500–3,000 ha^{-1}, thereby increasing the profit margin of farmers. In addition, the development of resistance against the commonly used herbicide isoproturon in *Phalaris minor* was also responsible for its adoption in the rice-wheat system because of the lower incidence of this weed under ZT.

The work on ZT began with the development of a ZT machine by Dr. Bachan Singh and his group in 1992-93. The area under ZT was negligible till 1996-97, when it slowly increased to 0.2 million hectares in 2001-02. Thereafter, the increase was very fast, with 0.5 million ha in 2002-03, around 1.0 million ha in 2003-04, to 2.03 million ha in 2004-05, including the area under reduced tillage. This shows how fast this technology was accepted by farmers of the rice-wheat area in the IGP. This was possible only because of the farmers' participatory approach adopted by the scientists working on this technology.

Time and diesel savings. The survey of villages around Karnal District in Haryana indicated that on average farmers were employing 12 tractor passes with various implements for sowing of wheat after rice harvesting. Using a drill for sowing of wheat after conventional field preparation requires two fewer tractor passes, whereas ZT requires only a single tractor pass. This resulted in savings of about 25% in time and 19% in fuel in conventional drill-sown wheat and the corresponding savings under ZT were about 88% and 93%, respectively (Table 1).

Table 1. Time and fuel consumption as influenced by different tillage options in wheat in farmers' fields.

Cropping practice	Tractor operations	Time (h ha^{-1})	Fuel (L ha^{-1})	Time savings (%)	Fuel savings (%)
Zero-tillage	1	1.6	6	87.6	92.5
Conventional tillage (drill)	10	9.1	65	25.1	18.8
Conventional broadcasting (farmers' practice)	12	12.6	80	–	–

Source: Sharma et al (2004).

Table 2. Comparative energy and economics of zero-tillage (ZT) versus conventional tillage (CT).

Parameter	ZT	CT	CT-broadcasting
Energy requirement (MJ ha^{-1})	20,279	23,136	23,631
Tillage cost (Rs. ha^{-1})	179	1,413	1,637
Grain yield (t ha^{-1})	5.6	5.6	5.4
Straw yield (t ha^{-1})	8.8	9.1	8.7
Gross income (Rs. ha^{-1})	43,251	43,732	42,405
Cost of production (Rs. ha^{-1})	26,023	27,578	27,860
Net income (Rs. ha^{-1})	17,228	16,154	14,545
Benefit-cost ratio	1.66	1.59	1.52
Specific energy (MJ kg^{-1})	1.41	1.58	1.68

Source: Sharma et al (2004).

Energy and economics. Considering the total cost of field preparation and drilling or broadcast sowing of wheat, it was found that the maximum cost was Rs. 1,637 ha^{-1} for broadcast-sown wheat, followed by drill-sown wheat (Rs. 1,413 ha^{-1}) (Table 2). The minimum cost was for ZT, which was only Rs. 179 ha^{-1}. The total energy required for various tillage options varied from 20,279 MJ ha^{-1} for ZT to 23,631 MJ ha^{-1} for broadcast-sown wheat. The benefit-cost ratio was highest for ZT wheat and lowest for broadcast-sown wheat, whereas the specific energy (energy spent per kg of biomass production) requirement was lowest for ZT wheat and highest for broadcast-sown wheat after conventional field preparation.

Effect on P. minor. A lower *P. minor* population and dry weight were observed under ZT compared with the conventional tillage system. Fewer weed problems under ZT may be due to less soil disturbance that helps keep weed seeds at a depth from which they cannot emerge. Unchecked weed growth during the crop season caused maximum yield loss in conventional tillage, followed by the furrow-irrigated raised-bed planting system, and ZT (Table 3). Therefore, ZT seems to be a cost-effective and sustainable weed management option.

Reduced/minimum tillage

The impact of ZT is that most farmers have shifted from intensive tillage undertaking 6 to 12 tractor operations to reduced tillage involving 2 to 3 operations with various farm implements. Reduced tillage has an advantage over conventional tillage as it saves on tillage cost, with similar

Table 3. Effect of tillage options and weed control practices on wheat.

Tillage option	Grain yield (t ha^{-1})		Weed dry wt. (g m^{-2})	Weed population m^{-2} in weedy check at 30 DAS
	Weedy check	Leader®		
Conventional	2.24	5.48	370	377
ZT	4.18	5.49	135	118
FIRBS	3.32	4.92	149	240

Source: Sharma et al (2004).

crop productivity. Reduced tillage has no apparent advantage over ZT, but farmers are sometimes forced to undertake 2 to 3 tractor operations for the following reasons:

- With some farmers, it is a problem of mind-set as they think that fields do not look tidy in the initial stages of crop growth.
- Early transplanting or using early-maturing varieties of rice vacates the fields by the first week of October, whereas sowing of wheat is generally done from the first week of November. In such fields, standing rice stubble becomes loose, which creates a problem for the smooth running of the ZT machine.
- Some broadleaf weeds, such as *Rumex* spp., germinate in October after the harvest of rice. Under such situations, a spray of glyphosate is recommended in ZT sowing of wheat. But it costs more than 1–2 plowings and also, because of the lack of proper spray techniques, some weeds are left after spraying. Therefore, farmers prefer 1–2 tillage operations instead of spraying.
- The field becomes uneven because of the formation of tracks in wet soil after combine harvesting. This happens either because of late irrigation or if rains occur toward the end of the rice season. If this happens, it becomes necessary to level those patches with 1 or 2 harrowings.

Bed planting

This water-saving technology saves 30–40% water for growing wheat depending on the soil type. In addition to saving water, this technology has numerous advantages in the rice-wheat system. Although there is no savings on the cost of land preparation or time, it can become cost-effective by using the same beds for rice without reshaping. In this technology, after land preparation, all three activities—bed formation, placement of fertilizer, and sowing of wheat—are done in a single operation. Crop cultivars are known to vary significantly in their performance on raised beds. Growing crops on raised beds is also suitable for seed production because of bolder grain and easier roguing. This reduces herbicide dependence because of mechanical weed control with the same bed planter fitted with interculture tines with simultaneous placement of fertilizer. In situations where sowing is delayed because of presowing irrigation, dry seeding can be done on raised beds, followed by irrigation immediately after seeding. Irrigation can also be given at the grain-filling stage, which farmers generally avoid for fear of crop lodging. In this technology, nitrogen-use efficiency is also higher because of light irrigation and topdressing on beds.

In a four-year study in farmers' fields around Karnal, the grain yield of wheat was around 6% higher under bed planting than under conventional flat-bed sowing by broadcasting (Table 4). The water applied at each irrigation was 45–50% lower in the bed system than with the conventional method of growing wheat.

Table 4. Results of trials conducted on raised-bed planting of wheat in farmers' fields in Karnal District.

Years	Location	Area (ha)	Seed rate (kg ha^{-1}, average of all locations)		Hours required for irrigating 1 ha with tubewell		Grain yield (t ha^{-1})	
			Bed	Conventional broadcast	Bed	Conventional broadcast	Bed	Conventional broadcast
1997-98	3	1.2	100.0	112.5	7	14	4.46	4.11
1998-99	8	6.0	98.5	110.0	5	9	5.20	5.00
1999-00	16	14.0	90.0	115.0	6	11	5.66	5.43
2000-01	9	20.0	87.5	122.5	6	12	5.82	5.51
Mean			94.0	115.0	6	11.2	5.29	5.01

Source: Samar et al (2002).

In another on-farm trial, different methods and time of sowing, nitrogen, and intercropping of sugarcane were tried on raised beds. For wheat, two lines per bed (37 cm wide) provided similar yield in timely sown wheat (Table 5). In late-sown conditions, three lines per bed performed better than two lines. Nitrogen topdressing on the bed was superior to broadcasting over the entire field, including beds and furrows. The nitrogen requirement in the bed system was around 30% less than in the conventional system. The other advantage of bed planting is that intercropping of sugarcane was possible with similar yield; otherwise, sugarcane is adversely affected when planted along with broadcast-sown wheat on flat beds.

Surface seeding

This technology does not require any field preparation and sowing of wheat is done in the standing rice crop a few days before or immediately after rice harvesting. There are areas in the eastern IGP where land remains wet after rice harvesting for a long time and field preparation for sowing a second crop is not possible. Under such conditions, surface seeding provides an opportunity to grow a wheat crop in the *rabi* season. Even in areas where field preparation is possible, wheat sowing is delayed, leading to very low yields. So, by adopting surface seeding, farmers can obtain higher yields.

In this technology, dry or soaked seeds are broadcast over the wet soil. To prevent bird damage, the seeds are invariably coated with cow dung. For a proper and uniform crop stand, drum seeders can also be usefully employed after rice harvesting. Nowadays, farmers are practicing surface seeding successfully not only in wheat but also in other upland crops such as pea, gram, lentil, etc.

In a two-year study that compared different tillage practices, Sen et al (2002) reported greater yield with surface seeding than with the conventional practice, although the differences were significant only in the first year (Table 6). The yield recorded was the highest in ZT wheat and lowest in the conventional practice. Weed density was significantly lower in ZT and surface seeding than in the conventional practice.

Table 5. Features of bed planting in wheat based on farmers' participatory research and experiments at the research station.

Sowing operation	Grain/cane yield (t ha^{-1})	
	Bed	Conventional
Sowing operations (av of two sites during 1998-99)		
Sowing in single operation	5.41	5.30
Sowing in double operation	5.43	–
Number of rows of wheat (av of two years, 1998-99 and 1999-2000, at research station)		
Sowing of two rows bed^{-1}		
1st week of November	5.75	5.50
1st week of December	5.36	–
Sowing of three rows bed^{-1}		
1st week of November	5.77	5.25
1st week of December	5.59	–
Nitrogen application methods (av of two years, 1999-2000 and 2000-01, of two locations each year)		
N topdressed on beds in two split doses		
98 kg ha^{-1}	5.91	–
128 kg ha^{-1}	6.03	–
N broadcast in two split doses		
98 kg ha^{-1}	5.53	–
128 kg ha^{-1}	5.91	–
Intercropping (results of one site during 1998-99)		
Sole crop of wheat	6.00	5.57
Wheat intercropped with sugarcane	5.84	–
Yield of autumn sugarcane intercropped with wheat	95.0	–

Source: Samar et al (2002).

Table 6. Effect of tillage practices on weed density at 60 d after seeding and grain yield of wheat.

Tillage practice	Weed density (no. m^{-2})		Grain yield (t ha^{-1})	
	1999-2000	2000-01	1999-2000	2000-01
Rotovator drill	51.0	88.3	3.72	2.39
Zero-till drill	32.7	65.7	3.93	2.56
Chinese drill	39.3	96.7	3.54	2.49
Surface seeding	59.0	84.3	2.95	1.81
Conventional (check)	65.7	120.5	2.51	1.48
CD (0.05)	11.7	14.0	4.23	4.68

Source: Sen et al (2002).

Direct dry-seeded and nonpuddled transplanted rice

In this system, rice is grown like any other upland crop, with seed placed in the soil by a seed-cum-fertilizer drill with or without plowing. The traditional practice of transplanting rice in puddled conditions requires a high amount of water and labor. In puddled soil, once the water dries, cracks develop and water along with nutrients percolates beyond the root zone. Generally, the plant population is 18–20 m^{-2} in manual transplanting versus the recommended density of 35–40 plants m^{-2}, which is a major constraint to achieving a higher yield of transplanted rice.

Direct seeding has advantages of faster and easier planting, reduced labor and less drudgery with earlier crop maturity by 7–10 days, more efficient water use and higher tolerance of water deficit, fewer methane emissions, and often higher profit in areas with an assured water supply. Thus, the area under direct-seeded rice has been increasing as farmers in Asia seek higher productivity and profitability to offset increasing costs and scarcity of farm labor (Balasubramanian and Hill 2002). Weed control is a major issue in direct-seeded rice and, to overcome this problem, intensive efforts are being made by agricultural scientists. In some soils, a spray of micronutrients such as zinc and iron may be needed to remove their deficiency.

Direct seeding of rice using a ZT drill, rotary-till drill, drum seeder, and broadcasting under various field preparation or puddling options was done at the Directorate of Wheat Research farm, Karnal, Haryana (Fig. 1). The rice variety used was IR64. Seeding depth was kept at 2–3 cm while using a drill for seeding. For comparison purposes, transplanting was also done under conventional

Fig. 1. Direct-drilled rice crop by zero-till and rotary-till drill.

Table 7. Rice yield (t ha^{-1}) under various crop establishment techniques.

Transplanting/ seeding option	Seeding conditions		Mean	Conventional puddling with harrow
	Zero-tillage	Rotary tillage		
Machine transplanting	6.73	6.77	6.75	6.88
Manual transplanting	6.67	6.75	6.71	6.92
Broadcast	4.93	6.66	5.80	
Drum seeder	5.57	6.13	5.85	
Direct drilling	6.59	6.68	6.64	
Mean	6.10	6.60		
CD (0.05)	Tillage = 1.47	Seeding = 3.28	Interaction = 4.64	

Source: Sharma et al (2003).

puddling as well as under ZT and after field preparation with a rotary tiller (Sharma et al 2003a,b). Direct seeding was done in the first week of June on the same day when the nursery was sown for transplanting. For weed control, pretilachlor (Sofit) at 1,500 mL ha^{-1} was applied 4 days after direct seeding, followed by one hand weeding at around 35 d after seeding.

Among the direct-seeding options, the yield was highest where rice was seeded using a rotary-till drill, followed by broadcasting sprouted rice seeds after field preparation by rotary tillage, and was lowest when rice was broadcast under ZT (Table 7). The mean yield in rotary tillage was higher than in ZT. Direct drilling by the ZT drill and rotary-till drill was on a par, and these two techniques were as good as transplanting under ZT or after field preparation by rotary tillage and were better than with drum seeding or broadcasting under ZT. Among transplanting and direct-seeding options, the highest yield was recorded in machine transplanting, which was significantly better than with broadcasting and the drum seeder but statistically on a par with other transplanting or seeding options. Yield was marginally higher in conventionally puddled conditions than in transplanting without tillage, after field preparation by rotary tillage, or in direct drilling with a zero- or rotary-till drill.

Direct wet-seeded rice

In this system, sprouted seeds are broadcast or placed with a drum seeder under puddled or nonpuddled conditions. Wet-seeded rice also reduces labor costs and effective herbicides for weed control have helped make this technology more popular. The seed rate in drum-seeded rice varies from 50 to 75 kg ha^{-1}, whereas, in the broadcasting method of seeding, 20–30 kg ha^{-1} is sufficient. In wet-seeded rice, puddling can be avoided without any adverse effect on rice yield. The observations in farmers' fields showed that mortality of sprouted seeds is higher under puddled conditions than under nonpuddled conditions.

A field trial on direct-seeded rice was conducted with different seed rates varying from 30 to 80 kg ha^{-1} during 2002. Similar yield was recorded, which suggests that the seed rate can be further reduced (Table 8). In the 2003 rice season, an additional treatment of 20 kg ha^{-1} was included. The varying seed rates were kept based on earlier recommendations of the Directorate of Rice Research at 75–100 kg ha^{-1}. The variety used was IR64 having a 1,000-grain weight of about 26 g. For a population of about 0.33×10^6 plants ha^{-1} recommended for transplanted rice, the seed requirement is likely to be around 11 kg ha^{-1} after an allowance for 20% loss in germination percentage of seed. If rodent and bird damage is added to the estimates, almost double the seed requirement (20 kg ha^{-1}) should be good enough. The trial was sown in the first week of July 2002

Table 8. Influence of seed rate on yield in direct-seeded rice.

Seed rate (kg ha^{-1})	Grain yield (t ha^{-1})	
	2002	2003
20	–	6.65
30	7.39	6.85
40	7.69	6.71
50	7.24	6.88
60	7.27	6.91
70	7.50	6.90
80	7.50	6.54

Source: Sharma et al (2003).

and the second week of July 2003, when transplanting is generally done. The yield recorded was similar at seed rates of 20 to 80 kg ha^{-1}.

Bed planting of rice

This technology has shown promise in wheat but the economic feasibility and long-term potential of the technology will depend on its success in both rice and wheat crops. The technology seems compatible and has the potential to reduce the cost of cultivation and improve the productivity of both crops along with natural resource conservation. To make the bed planting method effective in both rice and wheat, considerable additional research is required under both direct-seeded and transplanted rice situations.

The preliminary work done during *kharif* 2000 and 2001 in farmers' fields in two villages in Karnal District, Haryana, has shown that transplanting of rice on beds was better than the conventional flat-bed planting as it resulted in greater plant height, more panicles per unit area, larger panicles, and higher 1,000-grain weight, which led to higher grain yield (Singh et al 2002b) under sufficient water conditions (Table 9).

Weed management in DSR

Weed management is the major problem in DSR. Experiments have shown that it can be tackled successfully by integrated weed management practices, which include the stale-bed technique, crop rotation, ZT, use of competitive varieties, water management, mulching, intercropping of cover crops, and use of suitable chemicals at the right time. The integrated weed management approach uses all suitable techniques and methods, which maintains the weed population below the economic threshold level.

In the stale-bed technique, weeds are forced to germinate by applying irrigation and then killed by nonselective herbicides (paraquat or glyphosate at 0.5%) 2 to 3 d before seeding. This greatly reduces the seed bank in the soil. After seedling emergence, shallow submergence for 10–15 d does not allow germination of many weed species. Rotation with morphologically different crops with different growing requirements may help to break the cycle of adapted weeds. In the ZT system, not stirring up of the seed bank leads to a rapid reduction in weed population over time in many weed species. The practice of ZT allows the retention of previous crop residues in the field and it is well known that mulches are a good tool for weed management. Mulches normally exclude light and serve as a physical barrier to weed seedling emergence. In addition, they

Table 9. Effect of transplanting techniques on growth, yield attributes, and grain yield of rice in farmers' fields during 2000-01.

Transplanting technique	No. of plants m^{-2}		Plant height (cm)		No. of earheads (m^{-2})		Length of earhead (cm)		1,000-grain weight (g)		Paddy yield, (t ha^{-1})	
	2000	2001	2000	2001	2000	2001	2000	2001	2000	2001	2000	2001
Goghripur village												
Transplanting on raised beds	27	26	99.4	87.8	446	414	29.8	29.7	28.1	27.2	8.3	7.2
Transplanting in puddled conditions	24	21	98.2	86.2	432	398	27.2	28.4	26.2	26.1	7.0	6.7
Sultanpur village												
Transplanting on raised beds	–	31	–	101.2	–	462	–	27.6	–	–	–	9.0
Transplanting in flatbed without puddled conditions	–	30	–	104.2	–	467	–	27.8	–	–	–	8.9
Transplanting in puddled conditions	–	30	–	98.1	–	443	–	25.2	–	–	–	7.2

Source: Samar et al (2002).

also affect the soil temperature and moisture and add organic matter and nutrients to the soil after decomposition. Intercropping of *Sesbania* with direct-seeded rice suppresses weed infestation. It can be grown successfully without any adverse effect on rice yield when killed at 30 d after sowing (DAS) by 2,4-D at 500 g ha^{-1}. Being a legume crop, it also enhances soil fertility. So, promoting the use of cover crops enhances the sustainability of crop production and reduces weed density. Growing competitive varieties that suppress weeds is an essential component of integrated weed management. Studies have shown that rice cultivars such as PB-1 smother weeds to a great extent because of their early vigor and greater plant height.

Results of weed management trials conducted in farmers' fields in Karnal have shown that weed problems could be effectively tackled by growing *Sesbania* as an intercrop. It was observed that intercropping of *Sesbania* decreased weed density by 40% compared with the control plots. Growing of a cover crop like *Sesbania* along with rice does not require additional water and this practice not only reduces weed density but also adds nitrogen and organic matter to the soil. To evaluate the sowing time of a *Sesbania* intercrop with DSR, five trials were conducted in Kurukshetra District of Haryana in farmers' fields during *kharif* 2004. A seed rate of 25 kg ha^{-1} of *Sesbania* was broadcast 5 and 10 d after rice seeding and was killed 32 d after seeding with 2,4-D sprayed at 1.25 kg ha^{-1}. It was observed that sowing of *Sesbania* up to 5 d after rice seeding gave a significantly higher yield than a sole rice crop (Table 10).

Herbicides are becoming more widely available but farmers commonly lack awareness and information about how to use them correctly against diverse types of weed flora. Hence, chemical weed management in DSR is becoming knowledge-intensive. The following herbicides can be used for the control of weeds in ZT DSR:

- Preemergence application of pretilachlor with safener (Sofit) at 500 g a.i. ha^{-1} or pendimethalin at 1.0 kg a.i. ha^{-1} controls grassy weeds effectively. Pretilachlor requires stagnation of water for a few days for its full efficacy.

Table 10. Effect of intercropping of *Sesbania* sown at different times on weed density and grain yield of rice.

Treatment	No. of weeds m^{-2} (60 d)	Grain yield ($t\ ha^{-1}$)
Sole crop of rice	68	4.98
Sesbania sown at 0 d of rice	39	5.54
Sesbania sown at 5 d of rice	52	5.31
Sesbania sown at 10 d of rice	65	4.86
CD at (5%)	11	0.27

- Propanil at 175 g a.i. ha^{-1} or fenoxaprop ethyl at 50 g a.i. ha^{-1} or cyhalofop-butyl at 120 g a.i. ha^{-1} can be applied as a postemergence spray for the control of grassy weeds.
- To control broadleaf weeds, 2,4-D at 500 g a.i. ha^{-1} or Almix (chlorimuron + metsulfuron) at 4 g a.i. ha^{-1} can be applied after weed emergence.
- A tank mixture of fenoxaprop + ethoxysulfuron at 50 + 18 g a.i. ha^{-1} effectively controls both grassy and broadleaf weeds when applied postemergence.

Boro rice

Boro is a winter-season, photoperiod-sensitive, transplanted rice cultivated on supplemental irrigations. In some areas called *chaur* and *tal* lands in the eastern sector of the IGP, water accumulates during monsoon months and cannot be drained out in winter months. Boro rice is being cultivated in such areas. It takes advantage of residual moisture after the harvest of kharif rice. Boro rice is now also spreading to nontraditional areas in West Bengal, Bihar, and adjoining areas of Orissa and Andhra Pradesh. For boro cultivation, rice seedlings of a suitable variety are transplanted in mid-January to February in 5–6 cm of standing water at a spacing of 20 × 10 cm to maintain the optimum plant population. A fertilizer dose of 120–150 kg N, 60–75 kg P_2O_5, and 50–80 kg K_2O is required depending on soil conditions and need-based irrigations are applied. Boro rice has a yield potential of 6–7 t ha^{-1}.

The leaf color chart

Leaf color is a fairly good indicator of the nitrogen status of a plant. Nitrogen use can be optimized by matching its supply to crop demand as observed through a change in leaf chlorophyll content and leaf color. The leaf color chart developed by the International Rice Research Institute, Philippines, can help farmers because leaf color intensity relates to leaf nitrogen status in the rice plant. The monitoring of leaf color using a leaf color chart helps in determining the right time of nitrogen application. Use of the leaf color chart is simple, and cheap under all situations. Studies indicate that 10–15% nitrogen can be saved using the leaf color chart.

Laser land leveling

Laser land leveling is the process of smoothening of a field within ±2 mm from the average elevation using a laser-equipped bucket that scrapes soil from higher places and spreads it onto low-lying areas. Generally, fields are not properly leveled, leading to poor crop performance because part of the area suffers from water stress and part from excess water. It has been observed that yield increases 10–25% after laser leveling a field. The higher yields are due to proper crop stand, water distribution, crop growth, and uniform maturity. In addition to higher yield, savings of wa-

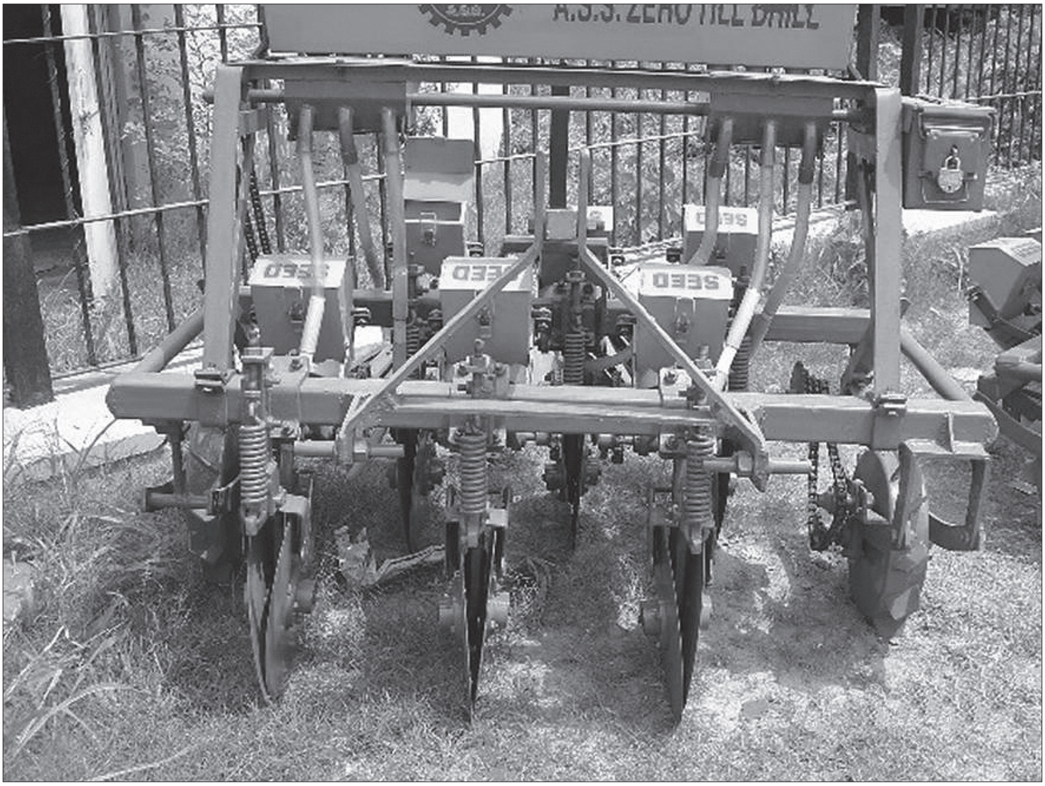

Fig. 2. Double-disc coulters.

ter are 35–45% because of the higher application efficiency and increased nutrient-use efficiency (15–25%). This technology reduces weed problems and increases cultivable area by 3–6% because of a reduction in area required for bunds and channels (Jat et al 2004).

New machines for residue management

Efforts are being made to develop suitable machines capable of seeding under loose residue conditions after combine harvesting. The need is felt because of the depletion of soil organic carbon and environmental pollution caused by burning of crop residues after combine harvesting. At present, four machines are being tested and evaluated for seeding direct-seeded rice and wheat, which are briefly discussed.

Double-disc coulters. This is one of the second-generation machines being tried under loose residue conditions (Fig. 2). It has double-disc coulters fitted in place of tines to place the seed and fertilizer into the loose residues. The problem faced by this machine is that being lightweight it fails to cut through the loose residues and the seed and fertilizer are dropped on top of it, part of which reach the soil surface. Irrigation is required immediately after seeding to facilitate germination. This machine may work up to a residue load of about 4–5 t ha^{-1}.

Punch planter/star wheel. This machine is being tested for seeding into loose residues (Fig. 3). It is being used widely around the world under nonrice situations but its utility under the rice-wheat system with a residue load of 6–10 t ha^{-1} is still to be proved. Initial results indicate that it may work under a low residue load of up to 3 t ha^{-1}. At present, this machine drops fertilizer on the

Fig. 3. The punch planter/star wheel.

surface in front of the moving star wheels, which is not the proper method of placing fertilizer.

Happy seeder. This machine cuts and lifts residues in front, places seed and fertilizer using a ZT machine, and drops the chopped straw behind onto the seeded area (Fig. 4). This machine is capable of seeding into a loose residue load of up to 10 t ha^{-1}. Recently, an improved version of this machine has been developed that cuts straw in strips of 5 cm only in front of the tines, which reduces the machine's energy requirement.

Rotary-disc drill (RDD). This machine is based on the rotary-till mechanism (Fig. 5). The rotor is a horizontal transverse shaft having six to nine flanges fitted with straight discs for a cutting effect similar to that of the wooden saw while rotating at 220 rpm. The rotary-disc drill is mounted on a three-point linkage system and is powered through the power take-off (PTO) shaft of the tractor. The rotating discs cut the residue and simultaneously make a narrow slit into the soil to facilitate placement of seed and fertilizer. The machine can be used for seeding under conditions of loose residues as well as anchored and residue-free conditions. If the machine is to be used under loose-residue conditions, it is better to use an offset double-disc assembly for placement of seed and fertilizer; otherwise, an inverted T-type or chisel-type opener can be used. The rotary-disc drill can also be easily converted into a rotary-till drill by replacing the discs with L- or J-shaped blades on the rotor. The rotor completely pulverizes the soil, leading to a clean and fine tilth. If a rotary-disc drill is to be used as a ZT drill, straight blades or discs can be used for minimal soil disturbance. However, it must be remembered that, in the presence of loose residues, a combination of a rotary disc with a coulter double disc completely avoids the raking problem of residues

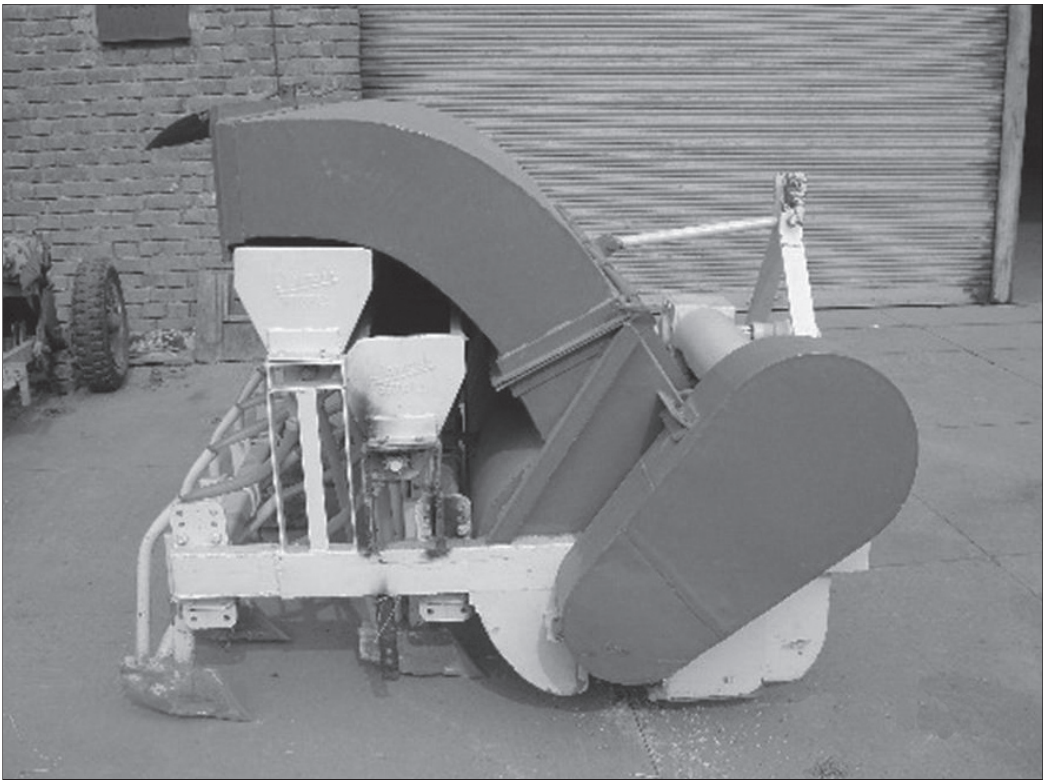

Fig. 4. The Happy seeder.

during seeding operations. Thus, the newly designed rotary-disc drill is a multipurpose machine, which can be used to seed under diverse situations depending upon the presence and condition of crop residues.

The rotary-disc drill can be used in manually harvested and combine-harvested fields for direct drilling of seed and fertilizer in a single tractor operation under variable field soil moisture conditions. Extensive field trials of the newly designed rotary-disc drill are already under way to determine the life expectancy of rotary discs. Direct-seeded rice using a rotary-disc drill was successfully established in 6 t ha^{-1} of loose residues of wheat. The machine was also tested in farmers' fields for its capability to sow under ZT as well as under loose-residue conditions, and the results were very encouraging.

Fig. 5. Rotary-disc drill (RDD). (A) Seeding into loose residue with RDD, (B) direct-seeded rice in loose residue.

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Rice and water sources and implications for direct seeding

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Water is a limited resource and competition is increasing for this scarce natural resource. Of the total available water on the globe, only 2.7% is fresh water, of which 75% is frozen in glaciers and snow cover. It is estimated that, by 2030, 62% of the globe will suffer from water scarcity. Rice flourishes in an abundant water environment that best differentiates it from all other important crops. It is the major consumer of water among all food grains—half of the total fresh water used for irrigation is consumed by rice. With traditional practices, 1 kg of rice is produced with 4,000 L of water, whereas wheat requires only 800 L of water to produce 1 kg of grain. Rice is more sensitive to water stress, particularly at panicle initiation and flowering stages. Among various rice cultures, field preparation in standing water, puddling, and transplanting require maximum water. In the Muda Irrigation Scheme in Malaysia, the yield per unit of irrigation water (g rice kg^{-1} water) was 0.75 for transplanted rice and 1.64 for dry-seeded rice with nearly equal total yield under the two systems. Similar observations were made at WTC, IARI, New Delhi. The total water requirement is thus less with direct-seeded rice (DSR) than with transplanting (TPR) and considerable savings in water can be achieved by adopting DSR. This practice has a low requirement of labor, water, and nutrient. The soil is not puddled, allowing the following aerobic crop not to suffer because of poor soil quality. DSR is more tolerant of water stress than TPR, which may be due to a superior root system. Water productivity of DSR is better than that of TPR and yields under the two systems are on a par, provided weeds are adequately controlled. Even in TPR, 20–30% savings of water can be made by avoiding continuous flooding and irrigating rice only 1 to 3 days after the disappearance of ponded water. Alternative methods of water management such as aerobic rice and low-energy water application have been discussed. For such systems, there is a need to study varietal responses, identifying preferred plant type characteristics, nutrient dynamics, and microbial diversity.

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Rice varieties for direct seeding

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The area under direct-seeded rice has been increasing in Asia as an attractive alternative to transplanting. Direct seeding reduces labor required for nursery preparation and manual transplanting and thereby reduces costs. Although labor and costs decrease, certain other technologies are required to overcome the constraints imposed by direct seeding such as varietal choice, water management, stand establishment, and weed control. Direct seeding in rice is done by two methods, dry and wet seeding. Dry seeding is mostly practiced on rainfed lands, whereas wet seeding is followed on irrigated lands. Although AICRIP contributed to the release of 715 rice varieties (irrigated 356, rainfed 222, hills 36, semideepwater 30, deepwater 15, and saline-alkaline 19) for different ecologies in the country, hardly any varieties were bred for direct seeding. No systematic and concerted efforts were made to evaluate/develop varieties suitable for direct seeding. Under the CREMNET-IRRI-DRR (ICAR) project, several rice varieties were evaluated for direct seeding at DRR and also at other centers. Of the varieties found promising at various locations, IET 9994 and Vikas performed consistently with high yields. Preliminary screening of rice varieties to identify ones with seedling traits suitable for direct seeding was done at DRR. A few promising varieties, such as Vikas, Rasi, Krishna Hamsa, Tulasi, and Ghanteshwari, were found to possess high early seedling vigor and better establishment.

Timely planting and optimum plant population are among the major determinants of yield in rice. With increasing wages and nonavailability of labor at critical times of farm operations, both these requirements are often not met and as a result varieties remain far from expressing their genetic yield potential. Direct seeding offers the advantage of faster and easier planting, reduced labor and less drudgery, and 7–10 days' earlier crop maturity. In the vast lowlands of eastern India, direct seeding of short-duration rice gives enormous opportunities for another rice crop before the main *kharif* crop. Though direct seeding of rice is an ancient practice in India, suitable varieties and technologies are lacking, and the problems associated with direct seeding have not received as much attention as those of transplanted rice. For example, varieties with early seedling vigor, an efficient root system for better anchorage and establishment, weed competitiveness, submergence tolerance to survive untimely rainfall during stand establishment, drought tolerance to survive dry conditions during germination and also at late stages, and lodging resistance at maturity are to be identified or developed. Technologies for land preparation, precision leveling, and water and weed management also need to be developed.

Asian rice farmers are shifting to direct seeding to reduce labor input, drudgery in farming, and cultivation costs (De Datta and Flinn 1986). Increased availability of short-duration rice varieties and cost-efficient selective herbicides have encouraged farmers to try this new method of crop establishment of rice elsewhere in Asian countries. Dry seeding is being practiced in rainfed lowlands, uplands, and flood-prone areas while wet seeding has been a common practice in irrigated areas. Wet seeding, especially aerobic wet seeding, is increasingly practiced in irrigated and favorable rainfed lowlands and it has been a common practice in most developed countries because of high wages and scarcity of labor (Smith and Shaw 1996). In developing countries, direct seeding is adopted because of the migration of farm labor to nonfarm jobs and the consequent shortage of labor and high wages (Pandey 1995).

Although direct seeding has been practiced in some parts of the world for centuries, few efforts have been made to identify favorable and adoptable varieties suited for direct seeding. So far, all the 715 released varieties in India were bred mainly for transplanted conditions, with very few exceptions. Some of these varieties perform fairly well under direct seeding in favorable conditions but end up with lower grain yields. Therefore, specific varieties must be selected/developed with improved early seedling vigor, high weed competitiveness, a robust and efficient root system for better anchorage and establishment, and tolerance of drought and lodging.

Varieties for direct seeding

Rice varieties selected for direct seeding must have flexible but strong stems to resist lodging at maturity, along with resistance to major biotic stresses. These varieties should possess enhanced foliar growth to combat weeds at the vegetative stage, moderate tillering, less foliar growth, enhanced assimilate export from leaves to stems during the late vegetative and reproductive phases, sustained high foliar N concentration at the reproductive stage, and improved reproductive sink capacity with a prolonged ripening period (Dingkuhn et al 1991). Though some of the derivatives of improved tropical japonicas possess some of these traits, they have to be evaluated under direct-seeding conditions.

Seedling establishment under anaerobic seeding may be controlled by interaction of environmental and management factors, plant physiological characters, and seed vigor (Yamauchi et al 1993). For example, rice varieties such as Mutant-2, New Bonet, IR54, and PR 103-80-1-2 have been selected for direct seeding in the Tanar Delta irrigation project of Kenya (Matsushima 1995). Similarly, the DRR has identified some varieties suitable for direct seeding in puddled soil in irrigated areas of India through coordinated agronomic trials (Table 1). For wet seeding, varieties ADT-36 and IET 9221 at Aduthurai; ADT 36 and ASD 16 at Coimbatore (Tamil Nadu); Jalpriya and Vikas at Ghaghraghat (Uttar Pradesh); Saket-4 and IET 9994 at Pusa (Bihar); Vikas and Luit in Assam; Vikas and IET 9994 at Hyderabad (Andhra Pradesh); and IET 9994 at Mandya (Karnataka) recorded the best results (DRR 1994). Overall, IET 9994 and Vikas had consistently high yields at many locations (DRR 1995). Another variety identified through on-station trials at Mandya is BR2655 for direct seeding in Karnataka State. Research is still needed to develop a suitable plant type for direct-seeding conditions in different ecosystems (Dingkuhn et al 1991). Averaged over several locations and years, row seeding with a drum seeder was superior to broadcasting. The mean increase in yield for the row-seeded crop was 7% higher than that of the broadcast method.

Table 1. Grain yield (t ha^{-1}) of different varieties under wet seeding in the DRR coordinated trials during the rainy kharif season.

Variety	DRR farm	Aduthurai	Coimbatore	Mandya	Chinsurah	Pusa	Ghaghraghat	Titabar	Mean
Vikas	5.07	3.23	6.45	4.37	3.63	3.10	3.45	3.44	4.18
IET 9978	4.90	4.63	6.25	4.91	3.28	3.02	3.17	3.26	4.18
IET 9994	5.56	3.70	5.98	4.41	3.06	3.09	2.88	3.12	3.98
IET 9221	5.08	4.61	5.32*[a]	4.69	2.64	2.69	2.43	2.22*	3.70
Local check	4.99	4.88	6.48	–	–	3.21	3.63	2.54	4.29
LSD (0.05)	0.67	0.11	0.09	ns	0.04	0.16	0.16	0.54	–
Name of local check	Rasi	ADT 36	ADT 36	–	–	Saket 4	Jalpriya	Lachit	–

[a]* = mean over 8 locations. ns = nonsignificant.
Source: Subbaiah and Balasubramanian (2000).

Varietal performance

Field trials on rice were conducted during the dry and wet seasons of 1993 and 1994 to evaluate varietal differences in terms of growth and grain yield under two methods of crop establishment at the experimental farm of the Directorate of Rice Research at Rajendranagar (Andhra Pradesh). Twelve varieties—Tulasi, IET 7959, Vikas, IET 10402, IET 9978, IET 7987, Rasi, IET 9221, Prassana, HKR 228, Pusa 615, and RP 2144—were tested under direct-seeded and transplanted conditions. Methods of establishment did not influence grain yield, whereas varieties differed significantly during both seasons. The mean maximum grain yield of 4.86 t ha^{-1} was recorded with Tulasi, followed by IET 7959 (4.6 t ha^{-1}), IET 9978 (4.56 t ha^{-1}), Rasi (4.47 t ha^{-1}), Vikas (4.45 t ha^{-1}), and IET 7987 (4.26 t ha^{-1}), and the lowest grain yield (3.77 t ha^{-1}) was recorded with RP 2144. Under direct-seeded conditions, varieties Rasi, IET 9978, Vikas, RP 2144, and Pusa 6155 recorded higher grain yield, whereas, under transplanted conditions, varieties IET 10402, IET 7987, and IET 9221 performed better. In another study by DRR, conducted during 1994 and 1995 to identify varieties suitable for direct seeding in puddled soils in the irrigated areas, a few varieties were found promising for wet seeding. Varieties ADT 36 at Aduthurai and Coimbatore (Tamil Nadu); Vikas and Jalpriya at Ghaghraghat (Uttar Pradesh); Vikas, Saket-4, and IET 9994 (Nidhi) at Pusa (Bihar); Vikas at Titabar (Assam); and Vikas and IET 9994 at DRR (Andhra Pradesh) performed better under wet-seeded conditions (Table 1). The two-year study indicated that Vikas and IET 9994 consistently gave the best results (DRR 1995).

During kharif 2000, 23 varieties were tested under direct-seeded and transplanted conditions to find out their suitability. Among the varieties tested, Tulasi, Tellahamsa, IET 9994, IET 9219, Vikas, and IET 11771 appeared to be well suited for direct seeding since they recorded higher grain yield under direct-seeded puddled conditions with a row-seeder than under transplanted conditions. The grain yield differences among varieties, on the other hand, were significant. IET 11689 and IET 9621 recorded a mean grain yield of 6.22 t ha^{-1}, followed by Tellahamsa (5.81 t ha^{-1}), IET 8887 (5.61 t ha^{-1}), Pusa Basmati 1 (5.6 t ha^{-1}), IET 9994 (5.58 t ha^{-1}), and Rasi (5.57 t ha^{-1}).

During rabi 2000-01, six varieties—Vikas, Ghanteshwari, Urvasi, Ruchi, Subhadra, and Nidhi—were tested under a standard package of practices under wet-seeded conditions. The grain yield differences among varieties were nonsignificant; however, numerically maximum grain yield was recorded by Nidhi (5.21 t ha^{-1}), followed by Subhadra (5.08 t ha^{-1}), Vikas (5.0 t ha^{-1}), Ruchi (4.93 t ha^{-1}), Urvasi (4.79 t ha^{-1}), and Ghanteshwari (4.71 t ha^{-1}).

Another preliminary study conducted at DRR involving 220 rice varieties to identify suitable seedling traits for direct seeding revealed that 32 varieties were superior for direct seeding based on high early seedling vigor and emergence score, fast growth rate (rate of germination), and efficient root system for better anchorage and establishment. Further, these selected varieties were evaluated under two methods of crop establishment—broadcasting of sprouted seeds and transplanting under puddled conditions. Varieties Tulasi, Vikas, Krishna Hamsa, Rasi, Tulasi, Ghanteshwari, and Triguna performed better than the remaining varieties, whereas Chetan, Safri 17, and Prasanna exhibited lodging. Further studies are being continued to confirm the results. However, systematic and concerted efforts are required to identify or develop suitable varieties for direct seeding.

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Quality of direct-seeded rice varieties and the effect of planting method on rice quality

Pratibha Singh, Govindra Singh, and V.P. Singh

Rice varieties were evaluated for their physical and cooking quality characteristics in field trials conducted at Pantnagar. The analysis of grain of 21 varieties during 2002 and 2003 showed that varieties had considerable variation in different quality traits. Varieties Nidhi, UPRI-92-79, UPRI-95-49, Narendra-359, and PD 6 had high milling yield. Head rice recovery was high in PD 6, UPRI-92-79, Narendra-359, and Nidhi. Thus, overall, from a miller's point of view, Nidhi, UPRI-92-79, Narendra-359, and PD 6 were preferred. Kernels of these varieties were cylindrical in shape. On cooking, kernel elongation was higher in Manhar, PD 6, WITA 4, WITA 3, Narendra-359, IR64, and Nidhi. Considering the grain yield and quality traits of these varieties, Nidhi and Narendra-359 turned out to be the most suitable for direct seeding. Amylose content in Nidhi was intermediate to high but was low in Narendra-359.

Quality studies of grain were undertaken in rice grain obtained from trials on methods of rice establishment. These trials were conducted for three years at Pantnagar and one season each (kharif 2003) at Kumarganj, Masoda, and Bikramganj. Physical quality of the grain-milling characteristics and size and shape of grains were little affected by the four methods of establishment—transplanting, wet seeding, direct drilling, and zero-till drilling. At Bikramganj, in variety Rajendra Mehsuri-1, head rice recovery was higher in dry or wet direct seeding. In cooking quality, the effect was seen mostly in amylose content in grain and water uptake on cooking. In three out of six data sets, amylose content was higher in grains of a transplanted crop than with a direct-seeded crop.

In rice (*Oryza sativa* L.), grain quality is more important than in many other cereals. In trade, rice quality is well recognized and marketability of rice depends partly on its quality (IRRI 1998). There are different standards of quality and price is determined by quality (Efferson 1985, Kaosa-ard and Juliano 1991). The concept of quality varies according to different perceptions. Some quality characteristics desired by growers, millers, and consumers might be the same, yet each may place different emphasis on the various quality characteristics. For example, millers' basis of quality depends on total recovery and the proportion of head and broken rice on milling. Cooking quality preferences vary in different countries and also among ethnic groups (Juliano et al 1964, Azeez and Shafi 1966, Juliano and Villareal 1993). Quality preferences in rice are so specific that farmers continue to grow many local types, which have quality characteristics of their liking, and farmers are reluctant to replace these low-yielding traditional types by high-yielding varieties. In India, high-yielding rice varieties cover only 54% of the total rice area (Nanda et al 1993).

With improved economic conditions and better standards of living, people are looking for better-quality rice. It is well documented that as income increases, significant changes occur in dietary patterns (Bouis 1989, Marks and Yately 1988). With increased income, consumers desire to improve the quality of their diet. With the abundant world rice supply and self-sufficiency in most rice-growing countries, emphasis is shifting from productivity to grain quality (Kaosa-ard and Juliano 1991, Unneveher et al 1985). Future varieties should have good potential head rice recovery and reduced amylose content. Improvement in grain quality coupled with productivity will enhance export potential and help to sustain marketability in trade and commerce (Nanda et al 1993). The price of rice has declined in the world market and in several Asian countries since 1975 and this has increased demand for better-quality rice (Flinn and Unneveher 1985). Special attention is being paid in the IRRI breeding program to appropriate cooking quality, taste preferences, and milling recovery (Khush 2004)

Heredity is the major factor influencing rice quality characteristics (Khush et al 1979, Juliano and Duff 1991). At the same time, environmental variations during the crop growth period, harvesting methods, moisture content, drying, and postharvest processing also influence quality traits (Ali and Ojha 1976, Bhashyam and Srinivas 1984, Toquero et al 1976). The investigation reported in this paper had two major objectives: selecting rice varieties suitable for direct-seeded conditions and comparing different methods of rice establishment. Rice quality aspects of this investigation are presented here.

Quality characteristics of rice

Rice grain quality denotes different properties to various groups in the postharvest system (Juliano and Duff 1989). For farmers, grain quality refers to minimum moisture, microbial deterioration, and spoilage. Millers look for low moisture, varietal integrity, and high total and head milled rice yield. Market quality is mainly determined by physical properties such as length, width, translucency, and degree of milling, color, and age of milled rice. Cooking and eating qualities are particularly affected by amylose content, which correlates directly to volume expansion and water absorption during cooking and with hardness, whiteness, and dullness of cooked rice (Juliano 1985). Aroma is a very important trait in rice quality.

Hulling, milling, and head rice recovery

Milling yield is one of the most important criteria for millers. Rice should possess a high turnout of whole-grain rice and total milled rice (Webb 1985). The weight of hull as a percentage of the weight of rough rice ranges from 17% to 26% and generally this figure is 20–22% (Dela Cruz and Khush 2000, Van Ruiten 1985). Akita et al (1990) reported that hull weights of grain harvested from September to November were higher than those of grains harvested in other months. Short- and medium-grain types give 55–70% head rice after milling, whereas, in long-grain types, head rice is 30–50% (Chaudhary and Ghosh 1978). Head rice recovery may vary from as low as 25% to as high as 65%. Delay in threshing reduces head rice yield (Berrio and Perez 1989, Sajwan et al 1988). Moisture content has an important influence on head rice recovery and Lee et al (1989) reported the greatest recovery at 16% moisture and lowest at 18%.

A negative and significant relationship has been reported between head rice recovery and kernel length, whereas kernel breadth had no association with head rice yield (Chauhan and Nanda 1982). High-density grain also contributes to better test weight and head rice yield (Nanda et al

1993). Varietal differences influence milling (Govindaswami and Ghosh 1969). Variability in head rice recovery among varieties is due to differences in structure, composition, and packaging of starch granules in the endosperm (McCall et al 1953, Khush et al 1988).

Grain size and shape

Rice grain is marketed according to its size, shape, and appearance. Consumers prefer rice with a translucent endosperm and pay a premium price for it. Uniformity in physical dimensions such as grain length, breadth, shape, and weight are of prime importance. These characters are reported to be polygenic in inheritance (Jones et al 1955, Lin 1978, Somrith et al 1979). Preference for grain size and shape varies from one group of consumers to another. In general, long grains are preferred in India, but, in Southeast Asia, the demand is for medium to medium-long rice. In temperate areas, short-grain varieties prevail. There is a strong demand for long-grain rice on the international market (Dela Cruz and Khush 2000, Chauhan et al 1991).

Amylose content

Amylose content is a major determinant of eating and cooking qualities. It determines the texture of cooked rice (Juliano 1979). High-amylose rice cooks dry, flaky, and fluffy and has a high volume expansion but hardens rapidly on cooling. Most preferred rice varieties are those with intermediate amylose content (Chauhan et al 1991). High-amylose rice is found mainly in tropical countries and low-amylose rice in temperate countries (Juliano and Pauscal 1980). Amylose content is highly influenced by the time of crop maturity and the temperature at the time of grain filling and ripening (Dela Cruz et al 1989). Tenderness and stickiness of cooked rice inversely correlate with amylose content (Kaosa-ard and Juliano 1991). Rice varieties are grouped on the basis of their amylose content into waxy (0–2%), very low (3–9%), low (10–19%), intermediate (20–25%), and high (>25%) (Kumar and Khush 1986). Waxy rice is glossy and sticky, does not expand in volume, and remains firm when cooked.

Gel consistency

Rice varieties with similar amylose content may have different tenderness, which can be measured through gel consistency (Kaosa-ard and Juliano 1991). Cooked rice with soft gel consistency is tender. Gel consistency may be hard (26–40 mm), medium (41–60 mm), or soft (61–100 mm). All brown rice varieties have hard gel consistency (Pervez 1979).

Grain elongation

Lengthwise expansion without an increase in girth is considered a highly desirable trait in some high-quality rice. Basmati rice elongates 100% on cooking. Grain elongation appears to be a quantitative trait (Dela Cruz and Khush 2000).

Water absorption

Water absorption is determined by the increase in weight of rice during cooking (Juliano 1982). It correlates negatively with gelatinization temperature and optimum cooking time. Water absorption is also increased by adding broken rice kernels with head rice (Yanes and Ohtsuba 1985). The water absorption value is lower for short- and coarse-grain varieties, and long-grain varieties tend to absorb more water than the other grain types (Batcher et al 1957). Water uptake positively correlates with volume expansion, kernel elongation, alkali value, and amylose content (Chauhan et al 1991).

Aroma

Aromatic rice is preferred in some Asian countries, including India, and it fetches a premium price. The presence of aroma is one of the main quality determinants in basmati rice. The aroma in rice is due to several volatile compounds, chiefly 2-acetyl-1-pyrroline (Buttery et al 1983, Paule and Powers 1989). High temperature at the time of grain filling and ripening tends to reduce the aromatic compounds (Kim 1999).

Alkali score

The alkali test measures the ease of corrosion of the starch granules by potassium hydroxide and is inversely related to gelatinization temperature. Gelatinization temperature is the range of temperature when starch granules start to swell irreversibly in hot water, accompanied by a loss of birefringence and crystalinity (Juliano 1982, Hizukuri et al 1983). It reflects the relative porosity of the whole endosperm. Starchy endosperm is rated visually based on a 7-point numerical spreading scale. Crack-resistant grains have a higher gelatinization temperature, a lower alkali score, and longer cooking time (Bhashyam et al 1985).

Materials and methods

The investigations reported in this paper had two components: selection of varieties for direct seeding and comparison of different methods of rice establishment. Rice grain quality aspects are reported herein.

Selection of rice varieties for direct seeding

To select suitable varieties for direct-seeded conditions with high productivity, resistance to biotic stresses (diseases, insects, and weeds), and good grain quality, 65 germplasm accessions were collected from different sources. These were tested in a field trial conducted at Pantnagar during kharif 2001. Grains of all the varieties were tested for their physical and cooking qualities. Based on their suitability, 21 accessions were selected for testing in 2004. These 21 entries were tested in a randomized block design with four replications for two years (kharif 2002, 2003). Quality of grain samples from each plot was analyzed after a storage period of 4 months in each year. The quality characters analyzed were as below:

Physical qualities. These were hulling %, milling %, head rice recovery, grain length, grain breadth, and length-breadth ratio.

Cooking qualities. These were kernel length after cooking, kernel breadth after cooking, kernel elongation ratio, water uptake, gel consistency, amylose content, alkali score, and aroma.

IRRI rice quality testing procedures were followed for the above quality analysis (IRRI 1998).

Methods of rice establishment

A field trial comparing four different methods of establishment was conducted at G.B. Pant University of Agriculture and Technology, Pantnagar, for three years (kharif 2001, 2002, and 2003). The same was conducted at N.D. University of Agriculture and Technology, Kumarganj, Faizabad; Rice Research Station Masoda (NDUAT); and Irrigation Research Station Bikramganj (RAU Pusa), Bihar, for one season (kharif 2003). The four methods of rice establishment were

1. Transplanting (TP).
2. Direct sowing—drilling rice in pulverized soil at optimum moisture (DS).
3. Wet seeding—drum seeding on puddled beds (WS).
4. Zero-tillage—drilling rice by a zero-till drill without any prior tillage (ZT).

These treatments were replicated four times at all the locations. The rice variety used in this trial at Pantnagar during 2001 and 2002 was Sarju 52 and Narendra-359 during 2003. The variety used at Kumarganj and Masoda was Sarju 52 and at Bikramganj it was Rajendra Mehsuri-1. Samples of rough rice were collected from all the plots from the four locations. In the trial at Pantnagar, samples were collected in all three years. After storage of 4 months, all the samples were analyzed for all the quality characteristics mentioned above for the varietal trial with the same procedures.

Results and discussion

Varieties

Physical characteristics. Among the 21 varieties tested during the two years, considerable variations occurred in both physical and cooking quality (Tables 1, 2). In 2002, hulling percentage varied from 68.1 to 82.8. The lowest and highest values of milling percentage were 58.7 and 74.0. Head rice recovery varied from 50.5% to 64.9%. The varieties with a higher milling percentage were UPRI-92-79 > Nidhi > UPRI 93-63-2 > PD 6 > IET16615 > UPRI-95-49> WITA 3 > IR64 > Narendra-359 > Manhar, all of which had more than 66% milling yield. Head rice recovery for the top varieties was in the order PD 6 > UPRI 92-79 > Nidhi > Narendra-359 > WITA 7 > IET 16615 > UPRI-1230-9-2, and all these had more than 60% head rice recovery. In 2003, varieties with a higher percentage of hulling were Govind, UPRI-1561-6-3, Nidhi, PD 6, Aditya, UPRI-93-63-2, UPRI-92-79, and Manhar, all having more than 80%. The milling percentage ranged from 68.1 to 75.0. Varieties with a high milling yield were Govind, Nidhi, UPRI-1561-95-49, UPRI-92-79, Narendra-359, WITA 4, Aditya, and PD 6. All these varieties had more than 73% milling yield. For head rice recovery, the top-yielding varieties were PD 6, UPRI 92-79, WITA 4, Narendra-359, IET 16480, and Nidhi, all having more than 66% head rice. Thus, the testing of varieties for 2 years showed that in milling yield the top varieties were Nidhi, UPRI-92-79, UPRI-95-49, Narendra-359, and PD 6. Head rice recovery was high in PD 6, UPRI-92-79, Narendra-359, and Nidhi. Considering these two characteristics (milling and head rice recovery), Nidhi, UPRI-92-79, Narendra-359, and PD 6 were the most suitable varieties.

For appearance, the size and shape of the kernels matter most (Adair et al 1966). Though all the varieties tested were of coarse rice, the kernel length in 2002 was higher in UPRI-95-49 (6.5 mm) = IET 16615 > Nidhi = WITA 7 = UPRI-1230-9-2 = WITA 4 (6.3 mm). The ratio of kernel length and breadth was higher in WITA 7 (2.42) > Narendra 359 > Nidhi > UPRI-95-49 = IET 16615 (2.24 mm). In 2003, higher kernel length was recorded in WITA 7 (6.9 mm) > PD 6 = UPRI-93-63-2 = Aditya = IET 16613 > Nidhi = FARO 8 (6.6 mm). The ratio of kernel length and breadth was higher in UPRI 93-63-2 (3.52) > WITA 7 > Aditya > Govind > FARO 8 = IR64 (3.30). Thus, according to the criteria of Dela Cruz and Khush (2000), all the above varieties were slender in shape (length-breadth ratio over 3.0). A length-breadth ratio between 2.5 and 3 has been considered widely acceptable as long as the length is more than 6 mm (Kaul 1970). Thus, the above varieties would be well accepted in the market.

Cooking characteristics. Cooking and eating characteristics of milled rice are very much influenced by the amylose content in the rice grain (Sanjiva Rao et al 1952, Bhattacharya 2004, Cheaupun et al 2004). Among the varieties tested, a majority had intermediate (20–25%) and high (more than 25%) amylose content. Only a few varieties in the first year had low amylose and these were IET 16615 (15.15%), Narendra-359 (17.76%), Pusa 44 (18.87%), and WITA 4 (18.56%). Varieties with low amylose content also had lower water uptake. Kernel length of cooked rice was longest for Narendra-359 (10.1 mm) and IET 16613 (10.1 mm). These were followed by Manhar (9.9 mm), UPRI 92-79 (9.8 mm), UPRI-1230-9-2 (9.6 mm), and IET 16843 (9.0 mm). In 2003, kernel length of cooked rice was in the order UPRI-1230-9-2 > IET-16840 > Aditya > Narendra-

Table 1. Physical characteristics of rice varieties.[a]

Variety	Moisture %	Hulling %	Milling %	Head rice recovery %	1,000-grain wt. (g)	KL-UC (mm)	KB-UC (mm)	KL-KB ratio
2002								
FARO 8	12.2	75.5	65.7	57.5	25.24	5.6	3.1	1.81
WITA 7	15.0	75.6	67.0	61.7	20.65	6.3	2.6	2.42
UPRI-1230-9-2	13.1	76.3	64.9	60.5	22.63	6.3	3.2	1.97
WITA 3	17.3	74.8	67.9	55.0	21.53	6.1	3.1	1.97
UPRI-92-79	12.1	82.8	74.0	63.7	26.77	5.7	3.1	1.84
IET-16840	12.0	73.4	65.5	56.1	25.94	5.7	2.9	1.97
IET-16843	12.3	72.1	61.6	56.2	25.94	5.7	2.9	1.97
PD 6	12.1	75.8	68.5	64.9	26.31	5.6	2.8	2.00
Aditya	13.2	68.1	59.8	50.5	22.41	6.1	3.4	1.79
UPRI-95-49	13.2	77.7	68.3	58.5	26.20	6.5	2.9	2.24
Govind	12.1	76.6	62.3	53.0	24.40	5.7	3.2	1.78
UPRI-93-63-2	13.0	77.9	69.7	58.7	23.12	6.2	4.0	1.55
IET 16615	13.1	80.8	68.3	60.5	21.35	6.5	2.9	2.24
IET 16613	12.2	73.4	61.4	51.1	23.90	6.1	2.9	2.10
Pusa 44	12.0	74.5	60.5	51.1	23.53	6.1	3.0	2.03
Manhar	12.3	78.8	66.2	55.7	19.27	5.9	3.1	1.90
Narendra-359	13.1	76.4	67.2	62.3	24.58	5.9	2.6	2.27
IR64	12.1	77.0	67.3	59.5	23.88	5.8	3.5	1.66
Nidhi	12.3	79.0	70.0	63.6	23.06	6.3	2.8	2.25
WITA 4	12.2	78.6	67.9	59.7	25.58	6.3	3.2	1.97
UPRI-1561-6-3	13.1	69.4	58.7	52.2	22.30	4.1	3.0	1.37
Standard error of mean	0.8	2.1	1.6	1.7	1.62	1.0	0.2	–
LSD (5%)	1.3	3.4	2.6	2.8	2.65	1.6	0.3	–
2003								
FARO 8	14.8	77.5	72.1	62.0	23.06	6.6	2.0	3.30
WITA 7	13.5	77.6	70.1	64.7	23.88	6.9	2.0	3.45
UPRI-1230-9-2	12.4	78.9	71.0	63.8	23.90	6.3	2.1	3.00
WITA 3	12.5	79.1	70.6	60.8	21.35	6.2	2.1	2,95
UPRI-92-79	13.1	80.6	74.1	68.2	25.24	6.3	2.4	2.58
IET-16840	12.5	79.4	70.1	67.5	24.40	6.5	2.0	3.25
IET-16843	12.5	74.6	70.9	62.0	19.27	6.0	1.9	3.15
PD 6	13.5	81.9	73.1	69.5	26.77	6.7	2.3	2.91
Aditya	13.5	81.6	73.5	66.8	25.94	6.7	2.0	3.35
WITA 3	12.5	79.1	70.6	60.8	21.35	6.2	2.1	2,95
UPRI-92-79	13.1	80.6	74.1	68.2	25.24	6.3	2.4	2.58
IET-16840	12.5	79.4	70.1	67.5	24.40	6.5	2.0	3.25
IET-16843	12.5	74.6	70.9	62.0	19.27	6.0	1.9	3.15
PD-6	13.5	81.9	73.1	69.5	26.77	6.7	2.3	2.91
UPRI-95-49	12.8	78.5	74.3	63.8	24.50	5.6	2.3	2.43
Govind	11.7	83.0	75.0	67.1	20.65	6.3	1.9	3.31
UPRI-93-63-2	12.7	81.9	72.6	65.4	21.53	6.7	1.9	3.52
IET 16615	13.7	79.2	70.1	60.4	23.12	6.4	2.3	2.78
IET 16613	13.2	75.4	74.0	60.5	26.31	6.7	2.3	2.91
Pusa 44	14.3	75.2	68.1	60.8	22.30	6.4	2.3	2.78
Manhar	13.5	80.5	71.6	65.1	26.20	6.4	2.2	2.90
Narendra-359	13.7	76.1	74.1	67.8	25.94	6.5	2.3	2.82

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Table 1 continued.

Variety	Moisture %	Hulling %	Milling %	Head rice recovery %	1,000-grain wt. (g)	KL-UC (mm)	KB-UC (mm)	KL-KB ratio
IR64	12.8	78.7	71.0	65.5	23.53	6.6	2.0	3.30
Nidhi	12.4	81.6	74.4	66.7	25.58	6.6	2.3	2.86
WITA 4	14.7	80.3	73.6	68.2	22.41	6.1	2.2	2.77
UPRI 1561-6-3	12.8	82.1	74.3	60.2	22.63	5.1	2.3	2.21
Standard error of mean	0.6	2.4	2.0	1.6	1.12	0.2	0.1	–
LSD (5%)	1.0	3.9	3.3	2.6	1.84	0.3	0.2	–

[a]KL = kernel length, KB = kernel breadth, UC = uncooked.

Table 2. Cooking quality characteristics of rice varieties.[a]

Variety	KL-C (mm)	KB-C (mm)	KER	AS	Water uptake (mL)	Aroma	GC (mm)	Amylose content (%)
2002								
FARO 8	6.90	2.30	3.00	7	316.2	Nil	45.2	22.99
WITA 7	8.60	3.00	2.87	6	294.3	Nil	50.1	22.63
UPRI-1230-9-2	9.60	3.10	3.10	7	289.4	Nil	40.0	22.11
WITA 3	7.40	2.30	3.22	1	301.4	Nil	84.2	22.71
UPRI-92-79	9.80	3.40	2.88	7	291.0	Nil	83.6	21.11
IET-16840	7.60	2.60	2.92	2	368.4	Nil	45.2	27.38
IET-16843	9.00	3.00	3.00	4	294.1	Nil	95.1	20.82
PD 6	8.30	2.30	3.61	6	275.2	Nil	81.6	22.18
Aditya	8.90	3.00	2.97	6	321.3	Nil	75.6	24.36
UPRI-95-49	6.50	2.10	3.10	2	286.1	Nil	47.4	20.91
Govind	8.30	3.10	2.68	2	281.0	Nil	66.0	20.86
UPRI-93-63-2	7.30	2.80	2.61	3	383.1	Nil	75.0	28.85
IET 16615	7.30	2.40	3.04	1	246.4	Moderate	35.7	15.15
IET 16613	10.10	3.30	3.06	1	384.7	Nil	85.1	39.04
Pusa 44	9.20	3.40	2.71	4	257.2	Nil	43.6	18.87
Manhar	9.90	2.30	4.30	6	361.4	Nil	80.0	38.89
Narendra-359	10.10	3.20	3.16	6	254.3	Nil	70.3	17.76
IR64	8.80	2.80	3.14	7	314.5	Nil	62.2	27.70
Nidhi	8.00	2.60	3.08	7	317.3	Nil	47.4	29.65
WITA 4	8.50	2.40	3.54	7	263.1	Nil	40.5	18.56
UPR-1561-6-3	6.90	2.50	2.76	4	301.5	Nil	60.1	21.50
Standard error of mean	0.37	0.18	–	–	20.91	–	10.2	1.12
LSD (5%)	0.61	0.29	–	–	34.29	–	16.1	1.83
2003								
FARO-8	8.6	3.0	2.86	6	316.6	Nil	39.0	24.44
WITA-7	8.7	2.5	3.48	5	285.1	Nil	44.7	23.55
UPRI-1230-9-2	9.5	2.9	3.27	7	286.8	Nil	46.0	21.3
WITA-3	9.1	2.6	3.50	2	313.1	Nil	52.0	20.72

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Table 2 continued.

Variety	KL-C (mm)	KB-C (mm)	KER	AS	Water uptake (mL)	Aroma	GC (mm)	Amylose content (%)
UPRI-92-79	8.4	2.6	3.23	5	300.0	Nil	53.3	20.33
IET-16840	9.4	2.5	3.76	3	307.1	Nil	46.0	22.80
IET-16843	8.1	2.6	3.11	3	287.6	Nil	68.0	25.69
PD 6	8.1	2.9	2.79	5	282.6	Nil	54.7	23.24
Aditya	9.3	2.7	3.44	3	341.8	Nil	50.4	25.66
UPRI-95-49	7.8	3.0	2.60	3	251.7	Nil	68.0	20.40
Govind	8.9	2.8	3.17	2	379.2	Nil	59.6	22.60
UPRI-93-63-2	8.5	2.8	3.03	1	283.5	Moderate	62.5	24.27
IET-16615	8.4	2.8	3.00	2	296.3	Nil	41.0	19.45
IET-16613	8.8	2.6	3.38	2	303.6	Nil	44.7	22.11
Pusa-44	8.8	2.9	3.03	3	297.3	Nil	34.6	16.64
Manhar	8.6	3.0	2.86	4	220.1	Nil	49.0	20.36
Narendra-359	9.1	2.8	3.25	6	300.5	Nil	35.4	18.20
IR64	8.8	2.4	3.66	6	365.2	Nil	55.0	23.16
Nidhi	8.3	2.8	2.96	4	378.4	Nil	63.0	23.16
WITA-4	8.9	3.0	2.96	6	361.0	Nil	40.3	19.41
UPRI-1561-6-3	6.5	3.0	2.96	3	297.0	Nil	68.3	21.64
Standard error of mean	0.3	0.1	–	–	18.74	–	6.7	1.33
LSD (5%)	0.5	0.2	–	0.87	30.73	–	11.0	2.18

[a]KL = kernel length, KB = kernel breadth, C = cooked, KER = kernel elongation ratio, AS = alkali score, GC = gel consistency.

359 > WITA 3. Varieties with higher kernel elongation ratio in 2002 were Manhar > PD6 > WITA 4 > WITA 3 > Narendra-359 > IR64 > Nidhi, all having kernel elongation ratios above 3. Varieties with a higher kernel elongation ratio in 2003 were IET16840 > IR64 > WITA 3 > WITA 7 > Aditya > IET 16613.

Grain yield. Grain yield of different varieties ranged from 4.22 to 7.44 t ha^{-1} in 2002, 1.69 to 6.11 t ha^{-1} in 2003, and 3.88 to 6.66 t ha^{-1} in 2004 (Table 3). Thus, the overall yield was slightly lower in the second year (2003). In the first year, the top-ranking varieties were Wita 4, Narendra-359, Pusa-44, UPRI-1561-6-3, Nidhi, and IET-16613. High-yielding varieties in the second year were Nidhi, Pusa-44, Narendra-359, UPRI-95-49, Manhar, and Pant Dhan-6. In the third year, the high-yielding varieties were UPRI-95-49, UPRI-1561-6-3, Narendra-359, Govind, IET-16615, and Pant Dhan-6. On average over the 3 years, the top-ranking varieties were Narendra-359, UPRI-1561-6-3, Pusa-44, UPRI-95-49, Nidhi, Manhar, and UPRI-1230-9-2, all yielding more than 5.5 t ha^{-1}. The productivity of Nidhi was higher in the first two years, but it was low in the third year. Narendra-359 and Nidhi, which were high yielding, also had high milling and head rice recovery. Their grain length and shape were medium. Amylose content was low in Narendra-359 and medium in Nidhi. Nidhi is a relatively short-duration variety. Narendra-359 is a very popular variety. Considering these characteristics, Narendra-359 and Nidhi will be the most suitable varieties for direct sowing. These have an advantage in yield as well as quality. Quality is also good in UPRI-92-79, which yields above 5 t ha^{-1} on average.

Table 3. Grain yield of rice varieties (t ha^{-1}).

Variety	2002	2003	2004	Mean
Pant Dhan-6	4.22	5.04	6.22	5.16
UPRI-1230-9-2	6.22	4.49	5.79	5.50
Govind	5.54	3.78	6.52	5.28
Nidhi	6.22	6.11	4.21	5.51
Manhar	5.55	5.06	5.92	5.51
UPRI-95-49	5.46	5.07	6.71	5.74
IET-16613	6.22	3.85	5.86	5.31
IET-16615	5.78	4.20	6.38	5.45
IET-16840	4.88	3.53	3.93	4.11
IR64	5.88	3.25	5.16	4.76
UPRI-1561-6-3	6.66	4.58	6.66	5.96
Narendra-359	7.10	5.08	6.60	6.26
UPRI-93-63-2	4.78	3.63	4.59	4.33
WITA-4	7.44	3.90	4.98	5.44
IET-16843	5.78	3.57	4.98	4.61
Aditya	6.16	3.64	4.38	4.72
Pusa-44	6.67	5.16	4.69	5.84
UPRI-92-79	5.53	4.50	5.66	5.23
WITA-3	4.66	4.32	5.77	4.91
WITA-7	4.32	4.59	6.02	4.97
FARO-8	4.77	1.69	3.88	3.44
LSD (5%)	–	0.92	1.55	–

Methods of rice establishment

The four methods of rice establishment (transplanting, wet seeding, direct drilling, and zero-till drilling) were compared. For transplanting and wet seeding, the soil was puddled. Direct drilling after field preparation and without tillage (zero-tillage) was done at soil moisture optimum for germination.

The milling characteristics of rice were not much affected by the methods of crop establishment, except that, at Bikramganj, where variety Rajendra Mehsuri-1 of medium-long duration was sown, head rice recovery under direct seeding (dry or wet) was higher than in the transplanted crop (Table 4). At Masoda, the test weight of kernels was higher in the transplanted crop than in direct drilling or wet seeding. At other locations, it did not vary under different methods. The size and shape of kernels (length, breadth, length-breadth ratio) were not affected by planting methods.

The cooking quality of rice was also not affected much by crop establishment methods (Table 5). Only at Kumarganj was the length of cooked kernels higher from the transplanted crop. Out of the six sets of data, in three cases, amylose content was lower in the direct-seeded crop than in the grain from the transplanted crop. Low amylose content in direct seeding also had some negative effect on water uptake in cooking. The alkali score in all cases was high (6–7), which indicates that on cooking the kernels get completely dispersed and intermingled. Thus, in rice quality studies, lower amylose content under direct seeding appears to be of interest.

Table 4. Effect of methods of rice establishment on physical qualities of grain.[a]

Method of crop establishment	Moisture %	Hulling %	Milling %	HRR %	1,000-grain wt. (g)	KL-UC (mm)	KB-UC (mm)	KL-KB ratio
Pantnagar 2001								
DS	13.1	75.4	66.3	60.6	23.7	5.9	2.0	3.0
WS	13.6	74.9	66.1	60.8	24.1	6.1	2.2	2.9
ZT	12.8	76.2	68.0	61.4	22.9	6.0	2.2	2.8
TP	13.7	74.8	67.7	61.0	23.5	6.0	2.1	2.9
Standard error of mean	0.5	2.7	1.4	1.6	0.3	0.2	0.1	–
Pantnagar 2002								
DS	12.6	76.3	68.1	61.4	24.7	6.1	2.0	3.0
WS	12.4	77.8	69.4	62.0	25.3	6.1	2.0	3.0
ZT	13.0	76.9	67.3	62.1	24.2	6.3	2.1	3.0
TP	13.1	77.4	68.0	61.7	24.7	6.9	2.1	3.3
Standard error of mean	0.2	3.6	1.9	2.1	0.7	0.2	0.1	0.1
Pantnagar 2003								
DS	13.50	78.2	69.6	58.7	25.94	6.57	2.30	2.86
WS	13.47	79.0	70.2	61.4	26.72	6.70	2.20	3.04
ZT	13.50	77.6	69.6	57.6	26.23	6.70	2.22	3.01
TP	13.52	78.4	69.0	59.4	27.26	6.67	2.25	2.96
Standard error of mean	0.59	2.1	1.8	1.7	0.42	0.13	0.06	–
Kumarganj 2003								
DS	14.7	80.0	70.1	61.8	19.81	5.60	2.05	2.73
WS	14.5	78.6	67.6	61.4	22.65	5.45	2.20	2.48
ZT	14.5	79.3	68.7	59.6	21.56	5.45	2.10	2.60
TP	15.0	80.3	69.4	62.3	22.45	5.45	2.30	2.37
Standard error of mean	0.3	0.8	0.6	2.9	0.17	0.31	0.11	–
LSD 5%	ns	ns	ns	ns	0.75	ns	ns	–
Masoda 2003								
DS	14.1	79.0	69.4	56.8	23.43	5.7	2.35	2.43
WS	14.3	77.6	70.6	56.0	23.28	5.7	2.25	2.53
ZT	14.5	78.6	69.7	58.1	24.18	5.7	2.05	2.78
TP	14.0	78.1	71.0	57.4	25.03	5.7	2.10	2.71
Standard error of mean	0.3	1.5	1.7	1.4	0.86	0.1	0.08	–
LSD 5%	ns	ns	ns	ns	1.40	ns	ns	–
Bikramganj 2003								
DS	13.17	80.1	70.8	68.92	23.24	5.95	2.10	2.83
WS	12.35	81.0	71.4	68.24	23.27	5.80	2.07	2.80
ZT	12.75	79.6	70.6	62.18	23.15	5.92	2.05	2.89
TP	12.35	80.7	71.0	63.86	23.18	6.07	2.20	2.76
Standard error of mean	0.16	1.3	1.4	1.52	0.40	0.13	0.07	–
LSD 5%	ns	ns	ns	4.88	ns	ns	ns	–

[a]HRR = head rice recovery, KL = kernel length, KB = kernel breadth, UC = uncooked, ZT = zero-tillage, WS = wet seeding, TP = transplanting, DS = dry seeding, ns = nonsignificant.

Table 5. Effect of methods of rice establishment on cooking qualities of grain.[a]

Method of crop establishment	KL-C (mm)	KB-C (mm)	KER	AS	Water uptake (mL)	Aroma	GC (mm)	Amylose content (%)
Pantnagar 2001								
DS	8.7	3.1	2.8	6	390.4	Nil	45.6	38.6
WS	8.6	2.8	3.1	7	377.5	Nil	51.4	40.1
ZT	9.0	2.9	3.1	7	361.0	Nil	39.3	37.9
TP	8.8	2.8	3.2	7	384.2	Nil	38.5	41.4
Standard error of mean	0.3	0.2	–	–	6.9	–	1.2	1.8
LSD 5%	ns	ns	–	–	12.6	–	2.2	3.2
Pantnagar 2002								
DS	9.2	3.0	3.06	6	348.0	Nil	37.4	30.3
WS	8.4	3.0	2.80	6	314.0	Nil	41.4	31.9
ZT	8.1	2.9	2.79	6	269.5	Nil	43.1	27.7
TP	8.5	3.2	2.66	6	346.0	Nil	40.2	42.3
Standard error of mean	0.3	0.1	–	–	16.8	–	2.1	3.4
LSD 5%	ns	ns	–	–	27.5	–	ns	5.6
Pantnagar 2003								
DS	8.5	3.0	2.8	6	285.3	Nil	52.5	23.45
WS	8.8	2.8	3.1	6	271.5	Nil	47.0	23.39
ZT	8.6	3.0	2.9	6	256.4	Nil	52.7	23.35
TP	9.0	2.9	3.1	6	268.3	Nil	49.2	22.95
Standard error of mean	0.1	0.0	–	–	–	–	2.8	0.14
Kumarganj 2003								
DS	8.2	2.8	2.9	6	294.4	Nil	70.0	23.67
WS	8.4	3.0	2.8	6	289.2	Nil	77.5	23.37
ZT	8.1	2.7	3.0	6	305.0	Nil	70.0	23.25
TP	8.8	2.7	3.3	6	350.4	Nil	65.0	24.27
Standard error of mean	0.0	0.3	–	–	11.4	–	3.7	0.41
LSD 5%	0.3	ns	–	–	17.6	–	6.8	0.75
Masoda 2003								
DS	8.5	2.9	1.49	6	304.2	Nil	67.5	24.03
WS	8.5	2.9	1.49	6	278.2	Nil	71.0	23.20
ZT	8.5	2.8	1.49	6	284.6	Nil	57.5	24.48
TP	8.5	2.6	1.49	6	304.1	Nil	55.0	23.66
Standard error of mean	0.1	0.0	–	–	14.2	–	2.3	0.61
Bikramganj 2003								
DS	8.5	2.7	3.1	6	309.8	Nil	46.00	25.12
WS	8.8	2.9	3.0	7	301.2	Nil	44.75	25.18
ZT	8.4	2.8	3.0	7	303.2	Nil	49.50	25.17
TP	8.9	3.0	3.0	7	291.1	Nil	47.75	24.77
Standard error of mean	0.1	0.0	–	–	6.9	–	1.83	0.27

[a]KL = kernel length, KB = kernel breadth, C = cooked, KER = kernel elongation ratio, AS = alkali score, GC = gel consistency, ZT = zero-tillage, WS = wet seeding, TP = transplanting, DS = dry seeding.

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Notes

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Comparative studies of direct seeding for irrigated rice

Direct seeding and weed management in the irrigated rice-wheat production system

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The productivity of the rice-wheat rotation of the Indo-Gangetic Plains is critical to India's food security. In this system, transplanting rice into flooded fields gives the crop a major competitive advantage over weeds as the majority of the weeds are suppressed by the standing water. Rising costs of labor, high water use and energy required for nursery establishment, puddling of fields and transplanting, coupled with labor scarcity during the peak period of activity are the compelling factors to seek an alternative to transplanting of rice. Direct seeding of rice is an alternative that could reduce the labor requirements for crop establishment and the demand for irrigation water. Direct seeding would also allow earlier establishment and harvest of rice, which, in turn, would permit earlier sowing of a subsequent wheat crop, leading to higher wheat yields. The major challenge for direct-seeded rice, though, is effective weed management.

A series of field experiments was established to evaluate different direct-seeding and weed management options for rice and wheat. Over four years, yields of "wet" (pregerminated)-seeded rice in clean weeded plots were slightly higher (9%) than those of transplanted rice. The potential yield losses due to weeds in direct-seeded rice, either wet or dry, were, however, much greater than in transplanted rice. Conventional tillage (6–7 harrowings) after the rice harvest in preparation for a wheat crop gave no yield advantage over the zero-till system. There were no significant effects on wheat yield as a result of the different rice establishment methods in the preceding crop. Researcher-managed on-farm experiments compared rice growth after soil puddling, transplanting, and direct seeding. At on-farm sites, rice yields from direct-seeded rice were comparable with those of transplanted rice under weed-free conditions, though somewhat less under weedy conditions.

The rice-wheat rotation is the predominant cropping system in the Indo-Gangetic Plains and its productivity is critical to India's and the region's food security. Rice is transplanted after puddling the soil early in the monsoon season and, after the rice harvest, wheat is commonly sown after 4–8 conventional tillage operations. Transplanting of rice requires large amounts of labor and also substantial amounts of irrigation water for puddling operations. The period of rice establishment is one of the peak periods of demand for labor, which is often scarce. This, in turn, may result in delayed transplanting and reduced crop yields. There are concerns about sustainability related to soil puddling as, besides the large amount of water required, it also requires considerable energy and has a deleterious effect on soil structure, which may affect the subsequent wheat crop. Because of these factors, there have been concerns about the sustainability of the rice-wheat production system (Sinha et al 1998, Timsina and Connor 2001).

Direct seeding of rice could provide an alternative to transplanting and it offers the advantages of earlier establishment, reduced labor and drudgery, earlier crop maturity by 7–10 days, and reduced water use, and soil puddling is not necessary. Direct seeding of rice may also allow earlier establishment of the succeeding wheat crop (Giri 1998), reduced methane emissions, and higher profit in areas with an assured water supply (Balasubramanian and Hill 2002). To evaluate different establishment methods of rice-wheat, experiments were conducted over a four-year period.

Materials and methods

Field experiments were conducted at G.B. Pant University of Agriculture and Technology, Pantnagar, to study the effects of crop establishment methods and weed control options on weed and crop growth. These studies were complemented by on-farm trials to compare establishment methods in farmers' fields in Udham Singh Nagar, Rampur, Bareilly, and Nainital districts of Uttaranchal/Uttarkhand.

Crop establishment

A field experiment in *kharif* rice consisted of five rice establishment methods as main plots and three weed management practices as subplots. In the subsequent season (*rabi*), the wheat crop was established as either conventional or zero-tillage, arranged in strips. The complete experiment was a strip split-plot design and there were four replications. In the kharif season, the establishment treatments for rice were (1) conventional transplanted rice (TPR) using 20–25-day-old seedlings, (2) wet-seeded rice (WSR) with pregerminated seeds sown with a drum seeder on puddled soil, (3) dry-seeded rice (DSR) with seed drilled in conventionally tilled soil, (4) direct seeding with flush irrigation (DSFR) as for DSR but the final tillage operations were followed by a flush of irrigation, and (5) zero-tillage rice (ZTR) in which seeding was done without prior tillage using a zero-till drill after glyphosate at 0.5 kg a.i. ha^{-1} had been applied to the area 1 week before sowing.

A rice seeding rate of 50 kg ha^{-1} with a row spacing of 20 cm was used for all dry-seeded treatments (DSR, DSFR, ZTR), while 35 kg ha^{-1} was used for wet seeding. Direct seeding of rice was done in the last week of May to the first week of June after seedbed preparation. At the same time, a nursery was sown and the seedlings transplanted 21–25 days after seeding (DAS).

Weed management

Three weed control treatments were applied as subplot treatments: (1) herbicide plus two hand weedings (CW) at 30 and 60 DAS and (2) one hand weeding at 30 DAS (HW), and (3) a weedy control with no weed management (T0). The herbicide applied in CW differed according to the rice establishment method. For TPR, butachlor at 1.5 kg a.i. ha^{-1} was applied 2–3 days after transplanting (DAT); for WSR plots, anilophos at 0.4 kg a.i. ha^{-1} was applied 5–7 DAS; and, for DSR, DSFR, and ZTR, pendimethalin was applied at 1.0 kg a.i. ha^{-1} within 1–3 DAS.

The rice variety Sarju-52 was sown during kharif 2001 and 2002 and Narendra-359 during 2003 and 2004. Main plots were separated by double bunds to preserve differences in water regimes and changes in soil structure and weed seed bank. Weed and crop plant samples were taken from two places in each plot (0.25 m × 1.0 m quadrats) covering five rows. In T0 and HW subplots, samples were taken at 28, 56, and 84 DAS and at 28 DAS/DAT in CW subplots and in all plots at harvest.

After the rice harvest, wheat was sown with a "Pant Zero-Till Drill" in half of the main plot area, as a "strip" plot, without any tillage, and in the other half after a seedbed was prepared by 5–6 harrowings and 3 plankings. In zero-till plots, paraquat was applied at 0.5 kg a.i. ha^{-1} 1 week before sowing. Yield and yield components were recorded in 5 m^2 from the harvest area in each plot. In the first season, kharif 2000, the rice crop was planted very late due to the sudden onset of monsoon rains and hence the crop was very poor. Data for this season are not reported.

On-farm experiments

Paired plots (0.2 ha each) were selected on various locations in farmers' fields in different districts of the *tarai* region of Uttaranchal and western Uttar Pradesh at 6, 7, 20, and 21 locations during kharif 2001, 2002, 2003, and 2004, respectively. Dry seeding was practiced on one part with subsequent weed management using pendimethalin at 1.0 kg a.i. ha^{-1} followed by hand weeding at 30 DAS. Transplanting (TPR) was done on the second part with butachlor at 1.5 kg a.i. ha^{-1} followed by hand weeding at 30–40 DAT. Within each establishment method, plots of 5 × 4 m^2 were marked at two places and in these plots no weed control was practiced. Weeds and crop plants were sampled from a 1-m^2 area at 28 DAS/DAT and their density and dry weight were recorded separately. Rice growth and yield were recorded from four quadrats of 5 m^2 each from each plot and from the weedy subplots. In the rabi season, the area was divided into two parts and wheat established after conventional tillage (CTW) and zero tillage (ZTW), and subsequent management of wheat followed standard local practices.

Results and discussion

Weeds

The common rice weeds in weedy plots (T0) were *Echinochloa colona, E. crus-galli, Eleusine indica, Eragrostis japonica, Ischaemum rugosum, Leptochloa chinensis, Dactyloctenium aegyptium, Digitaria sanguinalis, Cyperus rotundus, C. difformis, Fimbristylis miliacea, Caesulia axillaris, Commelina diffusa*, and *Eclipta alba*. (See V.P. Singh et al in this volume for a discussion on weed shifts.)

Yield components

The highest panicle density of rice was recorded in the clean weeded WSR while the dry-seeded treatments gave a number similar to transplanting (Table 1). In the T0 plots, however, WSR and DSR had about one-third the panicle density of TPR. Weed competition in the HW plots reduced panicle number by up to 30% compared with CW plots with the same establishment method. Weed competition in the HW treatment significantly reduced the number of grains per panicle compared with CW plots only in DSR, but grain numbers declined by more than half in the T0 plots of DSFR and ZTR. Although 1,000-grain weight decreased only slightly in TPR by weed competition in T0, it declined sharply in the dry-seeded plots (DSR, DSFR, ZTR).

Rice yield

The highest grain yields of rice were obtained from the clean weeded plots (CW) of wet-seeded rice in all seasons (Table 2); however, these yields were similar to those from TPR. The levels of yield losses varied between years and were particularly severe in 2001. Yield losses were markedly lower where weeds were not controlled and in dry-seeded plots; in some years, yield losses were

Table 1. Effects of rice establishment and weed management on yield components of rice (pooled data, 2001-04).

Rice establishment[a]	Panicles m^{-2b}			Grains per panicle			1,000-grain weight (g)		
	Weed management								
	T0	HW	CW	T0	HW	CW	T0	HW	CW
TPR	200	212	235	152	164	192	25.0	25.7	26.7
WSR	72	246	281	124	152	149	24.7	26.2	26.9
DSR	63	203	247	126	128	173	16.6	23.2	27.1
DSFR	38	164	225	65	164	160	13.3	26.6	26.2
ZTR	5	191	230	65	152	163	12.8	25.0	26.6
S.E.		14.0			14.4			0.63	

[a]See text for details. [b]Years 2002-04 only.

Table 2. The effects of rice establishment methods and weed management on rice yield (t ha^{-1}).

Rice establishment[a]	Year/weed management											
	2001			2002			2003			2004		
	T0	HW	CW	T0	HW	CW	T0	HW	CW	T0	HW	CW
TPR	5.89	7.23	7.85	4.56	5.54	6.14	4.98	4.97	5.33	6.71	6.50	6.84
WSR	1.03	5.61	8.14	0.95	5.44	6.76	0.33	5.49	6.39	2.25	5.95	7.13
DSR	0.0	1.02	6.11	0.99	5.08	6.69	0.0	4.77	5.52	1.97	5.36	5.93
DSFR	0.0	1.61	6.62	0.36	4.73	6.11	0.0	4.72	5.42	2.39	4.77	6.36
ZTR	0.0	1.52	6.60	0.15	5.38	5.74	0.0	4.85	5.09	0.33	3.87	5.31
S.E.		0.067			0.326			0.381			0.449	

[a]See text for details.

complete. In transplanted rice, yield losses were limited to about 25% in the T0 plots. The effect of one hand weeding in dry direct-seeded rice (DSR, DSFR, ZTR) varied across years, with yield losses of more than 75% in 2001 to less than 30% in 2004. Mukhopadhyay et al (1973) reported that serious weed infestation may lead to similar reductions (74–90%) in rice yield.

In our studies, herbicide followed by two manual weedings reduced weed growth to negligible levels in 2003 and 2004. The integration of hand weeding and herbicide in weed control for yield protection was essential and the use of herbicide followed by supplemental hand weeding gave yield gains over a single manual weeding. These gains were highest in direct-seeded plots in all years. Representative gains are shown for 2004 (Table 3). Economically, the yield benefit of an early postemergence herbicide represented a return of 1:2.3–3 in simple cost-benefit terms.

There was no yield advantage in wheat whether the crop had been established after conventional soil tillage (CTW) or zero-tillage wheat (ZTW) (Table 4). Further, there were no significant residual effects of rice establishment on wheat yields. These results indicate that zero tillage for wheat could be an alternative to conventional tillage without incurring a yield penalty and enabling a savings in time and energy. Tripathi et al (1999) also recorded comparable yields of wheat from

Table 3. Rice yield (t ha^{-1}) in relation to establishment method and weed management.[a]

Wheat establishment	Rice establishment	Herbicide followed by hand weeding	One hand weeding at 28–30 DAS/DAT	Gain due to herbicide
Conventional cultivation	Transplanted	7.05	6.70	0.35
	Wet-seeded	7.03	5.95	1.08
	Drill-seeded	6.08	5.08	1.00
	Drill-seeded + flush irrigation	6.00	5.28	0.73
	Zero-tilled	5.38	3.88	1.50
Zero-tillage	Transplanted	6.63	6.30	0.33
	Wet-seeded	7.23	5.95	1.28
	Drill-seeded	5.78	5.65	1.25
	Drill-seeded + flush irrigation	6.73	4.27	2.46
	Zero-tilled	5.25	3.86	1.40

[a]Standard errors of differences of means for comparing means with the same level(s) of wheat establishment = 0.384, rice establishment = 0.287, different levels of rice and wheat establishment = 0.369.

Table 4. Effects of rice establishment method on grain yield (t ha^{-1}) of wheat after conventional and zero tillage.

Rice establishment method[a]	Years/wheat establishment method					
	2001-02		2002-03		2003-04	
	CTW	ZTW	CTW	ZTW	CTW	ZTW
TPR	3.93	4.01	3.34	2.92	4.22	3.90
WSR	3.76	4.12	3.61	3.08	4.01	3.75
DSR	3.89	3.77	3.71	3.58	4.23	3.86
DSFR	3.81	4.13	3.60	3.13	4.05	3.86
ZTR	3.84	4.07	5.58	3.13	4.11	3.78
S.E.	0.265 ns[b]		0.197 ns		0.212 ns	

[a]See text for details. [b]ns = nonsignificant.

zero and conventional tillage irrespective of different rice seeding/transplanting methods, while Singh et al (2000) reported that 0.2–0.3 t ha^{-1} more wheat grain yield can be achieved by the zero-tillage system over conventional tillage.

On-farm experiments

Yields of transplanted and direct-seeded rice were similar in 2003 and 2004 where weeds were controlled (Table 5). Yield losses in unweeded plots were, however, slightly higher in direct-seeded rice than in transplanted rice.

Table 5. Effect of crop establishment methods on grain yield (t ha^{-1}) of rice, mean of various locations in farmers' fields.[a]

Rice establishment	2003 (7)		2004 (21)	
	Year/weed management			
	TO	TC	TO	TC
TPR	3.61	5.16	4.35	6.01
DSR	3.15	5.20	3.47	6.05
S.E.	0.31		0.19	

[a]Numbers in parentheses show the number of on-farm trials conducted that year. TO = weedy, TC = weeded, TPR = transplanted rice, DSR = direct-seeded rice.

Table 6. Economics of rice and wheat under different establishment methods in the rice-wheat production system.

Establishment methods	Total cost of production (000 Rs. ha^{-1})	Gross returns (000 Rs. ha^{-1})	Net returns (000 Rs. ha^{-1})
DSR CTW	31.7	76.8	45.0
DSR ZTW	30.5	78.1	47.7
WSR CTW	35.3	76.4	41.0
WSR ZTW	32.9	78.2	45.3
TPR CTW	35.7	72.0	36.3
TPR ZTW	33.3	74.3	41.0

Costs and returns to production systems

Partial budget analyses on the data collected in the on-station experiment (2003 and 2004) were conducted for dry and wet direct-seeded rice and transplanted rice in combination with either zero or conventional tillage for wheat (Table 6). This showed that production costs were the least for the combination of dry direct-seeded rice and zero-till wheat and the most for the current farm practice of conventional tillage for wheat and transplanted rice. The highest gross returns were obtained from the combination of wet- or dry-seeded rice with zero-till wheat. The largest net returns were derived from dry direct-seeded rice and zero-till wheat, followed by wet-seeded rice in combination with zero-till wheat.

Conclusions

These studies demonstrate in station and farm experiments that direct-seeded rice can produce yields comparable with those of transplanted rice provided weeds are controlled. All the potential yield of direct-seeded rice, however, may be lost if weeds are not effectively controlled. In some years, losses due to weeds controlled by a single hand weeding were not as great as in other years, but, overall, the losses in direct-seeded plots with only a single hand weeding were about 30%. In simple economic terms, the additional level of weed control provided by a herbicide and a supplementary hand weeding gave a benefit:cost ratio of 2.3:3. There appeared to be no effect of the establishment method for wheat on wheat yields, and this suggests that costs could be reduced by using zero tillage rather than conventional tillage. Further, the rice establishment method did not appear to affect the subsequent wheat. The critical nature of weed control suggests that farmers will require a substantial amount of knowledge in order to make good decisions and, further, with repeated use of direct seeding, there are likely to be shifts in weed species that may require alternative management strategies in order to provide effective control (see Johnson and Mortimer on issues for weed management, this volume).

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Studies on direct seeding of rice, weed control, and tillage practices in the rice-wheat cropping system in eastern Uttar Pradesh

D.S. Yadav, Sushant, A.M. Mortimer, and D.E. Johnson

Field experiments were conducted on research farms and in farmers' fields during the *kharif* and *rabi* seasons of 2003-04 at Narendra Deva University of Agriculture and Technology, Kumarganj, Faizabad, to study the effect of different crop establishment methods and weed control on rice and wheat. In 2003, transplanting of rice gave the most grain yield, though with good weed control, by herbicide and hand weeding or hand weeding alone; yields were similar to those of either drum seeding with pregerminated seed or dry seeding with zero-tillage. In 2004, the best yields were again from transplanted rice, though where weeds were controlled these were similar to those from zero-tillage rice. Where weeds were not controlled, in either year, the lowest yields were obtained from dry-seeded rice after zero- or conventional tillage and, in these cases, yield losses exceeded 95%. The principal weeds were *Echinochloa colona, Cyperus rotundus, Cynodon dactylon, Commelina diffusa,* and *Ammannia baccifera*. In farmers' field trials, grain yield of rice in transplanted fields gave 15% more yield than dry-seeded fields in 2003 and 22% more in 2004. Grain yield of wheat after direct-seeded rice in farmers' fields was 8% greater than the wheat yield that followed crops of transplanted rice.

Rice-wheat is one of the most important cropping systems in India, occupying 10.5 million ha, and contributing about 25% of total food-grain production. In this system, about 33% of India's rice and 42% of the wheat are grown and 65% of the total fertilizer use is applied. Rice production systems are undergoing various changes, one of which is interest in a shift from transplanting to direct seeding as farmers seek alternatives to offset increasing costs. The main driving forces for this change are the rising wage rates, scarcity of water and labor, and at the same time the availability of options to manage weeds in direct-seeded rice. Low and falling prices of rice have benefited the poor people of India, but, for farmers, who are producers of rice, the price they get for their produce has fallen in real terms while production costs have increased. To cope with this cost-price squeeze, farmers are seeking alternatives to reduce production costs, by either increasing yield or reducing input costs or both. Direct seeding is one such intervention. Direct seeding obviates the need for timely availability of a large labor force for transplanting. Puddling soil in preparation for transplanting of rice has led to questions regarding the possible negative effects on soil health and the subsequent wheat crop, and also about the sustainability of the system. Transplanting of rice can also lead to delays in establishing the wheat crop, which may, in turn, result in a decline in productivity equivalent to 1–1.5% ha^{-1} day^{-1} for each day sowing is delayed after the end of November sowing (Ortiz-Monasterio et al 1994).

Direct-seeded rice is currently grown in India mainly in the unfavorable low-productivity systems and short-duration varieties are mostly grown in upland conditions. In favorable environments, mostly irrigated areas, transplanting is practiced. Farmers commonly face several constraints related to transplanted rice:

- Lack of timely labor availability
- Late rice planting
- Drudgery for farm workers
- Low rice plant populations
- High production costs
- High water use for puddling
- Restricted root system of wheat due to puddling for rice
- Adverse effects of puddling on soil physical conditions

India's agriculture has the problems of limited labor availability because of more off-farm jobs being created due to economic growth, putting pressure on supplies of agricultural labor. Alternate methods of rice establishment requiring less labor need to be developed to maintain the productivity of the systems. Direct seeding offers certain advantages although constraints are also associated with it.

The advantages of direct seeding are

- It saves labor at transplanting
- Faster and easier crop establishment
- It involves less drudgery
- Rice crops mature 7–10 days earlier than transplanted crops
- It requires less irrigation water
- Direct-seeded crops have a higher tolerance of water deficit
- It often has higher yield, a lower production cost, and more profit
- Soil physical conditions are better for following crops
- It produces less methane

Some constraints to direct seeding are

- Fields are occupied 2 weeks longer than for transplanted crops
- Higher weed pressure
- Good crop establishment may be difficult
- Precise water management and level fields are necessary
- Crop lodging may be greater
- Higher pest and disease incidence is likely in dense canopies because of less ventilation around plants
- More variability and risk

To address some of the above considerations, an agronomic evaluation was conducted of crop establishment methods in rice and wheat, and of weed control methods in rice.

Materials and methods

Field experiments were conducted during the *kharif* (wet) and *rabi* (cool) seasons in 2003-05. On-station experiments were conducted at the main campus of Kumarganj and at the crop research station in Masodha, Faizabad, on silty loam soil. The initial soil properties such as pH, electrical conductivity, organic carbon, and available N, P, and K of the experimental sites were 8.3, 0.42 dS m^{-1}, 0.44%, and 110, 14.4, and 290 kg ha^{-1} at Kumarganj and 7.2, 0.15 dS m^{-1}, 0.54%, and 132.5, 17.0, and 153 kg ha^{-1} at Masodha, respectively. The average annual rainfall of the area is about 1,000–1,200 mm.

The treatments consisted of four rice establishment methods as main plots: conventional transplanting after puddling (TPR), wet seeding with a drum seeder after puddling (WSR), dry drill seeding after conventional tillage (DSR), and dry drill seeding after zero-tillage following flush irrigation and glyphosate (ZTR). Four weed control methods were arranged as subplots: weedy check (WC_0); herbicide + 1 hand weeding at 30 days after sowing (DAS), WC_1; herbicide + 2 hand weedings at 30 and 60 DAS (WC_2); and hand weeding (twice) at 30 and 60 DAS (WC_3). In the kharif, plots were arranged in a split-plot design and replicated 4 times. In the rabi, the main plots were divided into "strips" to include tillage treatments—conventional and zero-tillage in preparation for wheat. The experimental design was a strip-split-plot design. Different herbicides were used with the various rice establishment methods: butachlor at 1.5 kg a.i. ha^{-1} in TPR at 3–4 days after transplanting (DAT), anilofos at 0.4 kg a.i. ha^{-1} in WSR at 8–10 DAS, and pendimethalin at 1.0 kg a.i. ha^{-1} in DSR and ZTR at 2–3 DAS in subplots (WC_1 and WC_2). Glyphosate (41%) at 4 L ha^{-1} was sprayed 2–3 days before sowing in zero-tillage plots of rice and wheat. Rice variety Sarju 52 and wheat PBW 343 were used. At Kumarganj, sowing of rice under WSR, DSR, and ZTR, and for nursery was done from 29 June to 1 July in 2003 and from 29 June to 3 July in 2004, whereas, at Masodha, this was done from 22 to 24 June in 2003 and from 23 to 25 June in 2004. For transplanting, two or three 25-day-old seedlings were used per hill. Sowing of wheat, at both locations, was done 25-26 November 2003 for zero-tillage and 5-6 December 2003 for conventional tillage. Fertilizer of N-P_2O_5-K_2O at 120-60-60 kg ha^{-1} for rice and 120-60-40 kg ha^{-1} for wheat was applied. Harvesting of rice was in the first week of November and of wheat in the third week of April during each year.

Results

Rice—2003 and 2004

There were no significant effects of the method of direct seeding on the rice plant density at 30 DAS at Masodha (WSR = 274, DSR = 290, and ZTR = 272 plants m^{-2}) or at Kumarganj (WSR = 216, DSR = 182, and ZTR = 191 plants m^{-2}).

At Masodha and Kumarganj, establishment method and weed control had significant effects ($P<0.001$) on the number of panicles per m^2 and the number of grains per panicle. Overall, transplanted rice had the most panicles and ZTR the least (Tables 1, 2). At Masodha, without weed control (WC_0), the number of panicles in DSR and ZTR was substantially lower than in TPR, whereas WSR was less affected. The number of grains per panicle followed a similar pattern as panicle density, though the differences between the direct-seeding treatments were not significant within any given weed control level (Tables 3, 4). ZTR rice took 2 days less to mature than DSR, and 4 and 8 days less than WSR and TPR at Masodha and 6 and 12 days less at Kumarganj (Tables 5, 6). Overall, TPR produced the most grain yield of the establishment methods but this was not significantly different from WSR except in WC_0, where there was no control of weeds and where WSR yield was only approximately 60% that of TPR (Tables 7, 8).

Weed growth in rice in 2003 and 2004

In 2003 at Kumarganj, among the direct-seeded treatments, total weed biomass at 30 DAS was least in the WSR plots and most in DSR, with the exception of the hand-weeded plots (Table 9). In

Table 1. Number of rice panicles per m² as influenced by method of establishment × weed management interaction, Masodha, kharif 2003.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	317	348	367	349	345
WSR	229	306	345	315	299
DSR	94	300	330	313	259
ZTR	79	267	298	267	228
Mean	180	305	335	311	

[a]S.E.D. for comparing main effects of establishment = 5.9, weed control = 7.0, and establishment × weed control = 13.4.

Table 2. Number of rice panicles per m² as influenced by method of establishment × weed management interaction, Kumarganj, kharif 2003.

Rice establishment				
TPR	WSR	DSR	ZTR	S.E.D.
307.6	272.4	199.2	201.6	12.24
Weed control				
WC_0	WC_1	WC_2	WC_3	S.E.D.
196.4	247.2	258.8	279.2	17.52

Table 3. Number of rice grains per panicle as influenced by method of establishment × weed management interaction, Masodha, kharif 2003.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	104.6	122.0	144.4	119.8	122.7
WSR	67.7	110.5	135.9	123.0	109.3
DSR	58.6	101.7	131.9	120.1	103.1
ZTR	53.3	109.1	130.4	122.1	103.7
Mean	71.1	110.8	135.7	121.3	

[a]S.E.D. for comparing main effects of establishment = 3.13, weed control = 3.26, and establishment × weed control = 6.46.

Table 4. Number of rice grains per panicle as influenced by method of establishment × weed management interaction, Kumarganj, kharif 2003.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	110.2	120.0	124.9	114.6	117.4
WSR	58.8	118.5	109.1	109.8	99.0
DSR	47.4	109.1	118.0	102.2	94.1
ZTR	49.1	131.7	128.2	123.1	108.0
Mean	66.4	119.8	120.1	112.4	

[a]S.E.D. for comparing main effects of establishment = 6.10, weed control = 7.18, and establishment × weed control = 13.86.

Table 5. The main effects of establishment method on days to rice maturity, Masodha, kharif 2003.

Rice establishment				S.E.D.
TPR	WSR	DSR	ZTR	
130.6	126.0	124.4	122.3	0.63

Table 6. The main effects of establishment method on days to rice maturity, Kumarganj, kharif 2003.

Rice establishment				S.E.D.
TPR	WSR	DSR	ZTR	
130.2	125.8	120.9	118.1	0.82

Table 7. Grain yield of rice (t ha^{-1}) as influenced by method of establishment × weed management interaction, Masodha, kharif 2003.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	3.28	4.04	4.90	4.36	4.15
WSR	1.98	3.77	4.52	4.14	3.60
DSR	0.36	2.93	3.87	3.29	2.61
ZTR	0.53	3.04	4.12	3.46	2.79
Mean	1.54	3.44	4.36	3.81	

[a]S.E.D. for comparing main effects of establishment = 0.188, weed control = 0.152, and establishment × weed control = 0.323.

Table 8. Grain yield of rice (t ha^{-1}) as influenced by method of establishment × weed management interaction, Kumarganj, kharif 2003.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	3.60	3.88	4.51	4.24	4.06
WSR	2.25	3.51	4.40	4.17	3.58
DSR	0.44	1.51	3.67	2.83	2.11
ZTR	0.32	2.43	3.93	3.59	2.57
Mean	1.65	2.83	4.13	3.71	

[a]S.E.D. for comparing main effects of establishment = 0.328, weed control = 0.196, and establishment × weed control = 0.471.

Table 9. Total weed dry matter (g m^{-2}) 30 days after sowing as influenced by method of establishment × weed management interaction, Kumarganj, kharif 2003.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	–	–	–	–	–
WSR	98.0	68.9	54.1	116.5	84.4
DSR	177.3	230.2	136.7	114.8	164.7
ZTR	112.4	187.4	70.3	205.0	143.8
Mean	101.8	130.0	78.0	114.0	

[a]S.E.D. for comparing main effects of establishment = 15.84, weed control = 13.28, and establishment × weed control = 25.45.

2004, there were no significant interaction effects and weed growth was greatest in ZTR and least in DSR and where there had been no control (WC_0) measures (Table 10).

The dominant weed species observed at Kumarganj were *Echinochloa colona, Cyperus rotundus, Cynodon dactylon, Commelina diffusa,* and *Ammannia baccifera*. Figure 1 shows the weed biomass at 30 DAS and rank order of the main species in the hand-weeded plots in 2003 and 2004 at Kumarganj. In both years, *C. rotundus, C. dactylon*, or *E. colona* accounted for the most biomass for each of the establishment methods. *C. diffusa,* having been present at the site in 2003, was of increased importance in 2004 in WSR and DSR, whereas *E. colona* dropped in its ranking in DSR. In all three establishment methods, a number of other species were recruited into the rice. The other weeds of potential concern present at the sites were *Ischaemum rugosum, Echinochloa crus-galli,* and *Paspalum distichum, Fimbristylis miliacea, Phyllanthus niruri, Eclipta alba, Lindernia* sp., *Corchorus* sp., and *Cyanotis axillaris*.

Wheat grain yield in 2003-04

There were no effects of rice and wheat establishment methods on grain yield of wheat at either site. The mean yield at Masodha was 3.6 t ha^{-1} and 4.0 t ha^{-1} at Kumarganj.

Table 10. Total weed dry matter (g m^{-2}) 30 days after sowing as influenced by method of establishment × weed management interaction, Kumarganj, kharif 2004.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	–	–	–	–	–
WSR	104.4	45.9	55.4	87.5	73.3
DSR	83.6	42.1	31.6	62.4	54.9
ZTR	180.2	74.0	53.3	82.1	97.4
Mean	122.7	54.0	46.8	77.3	

[a]S.E.D. for comparing main effects of establishment = 6.55, weed control = 12.50, and establishment × weed control = 19.86.

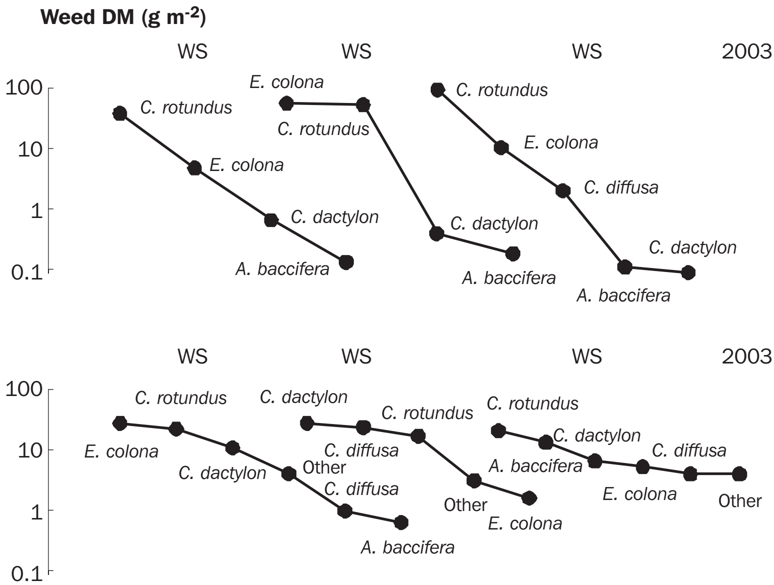

Fig. 1. Rank order of weed species biomass at 30 DAS in hand-weeded plots of rice after different establishment methods, kharif 2003 and 2004.

Grain yield in 2004

Rice grain yields for Masodha and Kumarganj for 2004 are shown in Tables 11 and 12. The patterns of response to treatments were similar at both sites. Yields from ZTR were as good as or better than with transplanted rice providing weeds were controlled and both ZTR and TPR gave better yields than DSR and WSR under these conditions. Where weeds were not controlled (WC_0), WSR gave less than half the yield of TPR and DSR, and ZTR yielded lower still.

Table 11. Grain yield of rice (t ha^{-1}) as influenced by method of establishment × weed management interaction, Masodha, kharif 2004.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	1.963	2.419	2.675	2.541	2.399
WSR	1.100	2.059	2.531	2.228	1.980
DSR	0.578	1.872	2.269	1.975	1.673
ZTR	0.472	2.325	2.800	2.569	2.041
Mean	1.028	2.169	2.569	2.328	

[a]S.E.D. for comparing main effects of establishment = 0.0345, weed control = 0.042, and establishment × weed control = 0.083.[a]

Table 12. Grain yield of rice (t ha^{-1}) as influenced by method of establishment × weed management interaction, Kumarganj, kharif 2004.[a]

Rice establishment	Weed control				Mean
	WC_0	WC_1	WC_2	WC_3	
TPR	3.047	3.325	3.678	3.466	3.379
WSR	1.416	2.941	3.041	2.628	2.506
DSR	0.853	2.806	3.316	2.669	2.411
ZTR	0.122	3.594	3.937	3.872	2.881
Mean	1.359	3.166	3.493	3.159	

[a]S.E.D. for comparing main effects of establishment = 0.185, weed control = 0.0907, and establishment × weed control = 0.144.

On-farm trials

Rice

In farmers' fields (13 fields) in 2003, the mean grain yield from TPR was 15% more than from direct-seeded rice (4.14 vs. 3.59, S.E. = 0.15). In 2004, transplanted rice yielded 22% more than direct-seeded rice; however, it can be seen (Fig. 2) that the mean values are strongly influenced by a few farm sites and, for the majority, the yield differences between direct seeding and transplanting were less that 10%. The lower yields under direct seeding might be due to either poor crop establishment or management of weeds in farmers' fields.

Wheat

Wheat was sown after direct-seeded and transplanted rice at 13 locations during 2003-04. Wheat grain yield after direct-seeded rice was 4.08 t ha^{-1} versus 3.77 t ha^{-1} after transplanted rice. This difference in yield may have been due to the earlier sowing of wheat after direct-seeded rice.

Discussion

Sankaran and De Datta (1985) reported an average yield loss in upland rice of 59%, whereas, in the second year of our studies, yield losses in zero-tillage rice with no subsequent weed control were

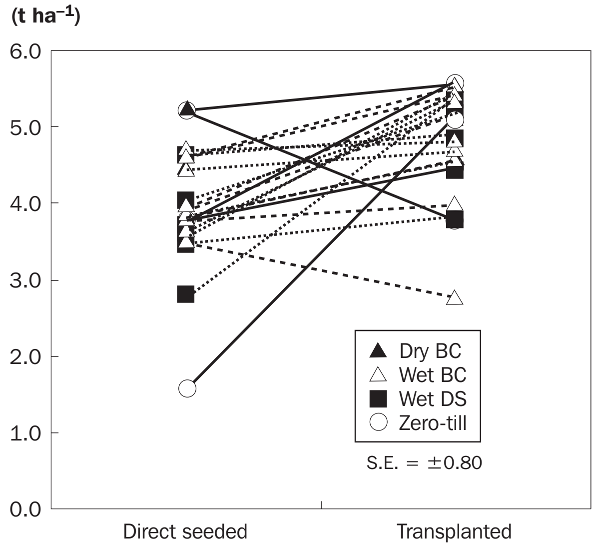

Fig. 2. Rice grain yield in on-farm trials (n = 22) comparing four direct-seeding methods with transplanting, Faizabad, kharif 2004. Dry BC = dry seed, broadcast after dry tillage, Wet BC = pregerminated seed broadcast on puddled soil, Wet DSR = pregerminated seed sown with drum seeder, Zero-till = dry seed sown with zero-tillage drill.

more than 95%. The highest grain yields were generally recorded with WC_2 (herbicide + 2 hand weedings), which suggests that a single follow-up weeding after herbicide treatment is not adequate to minimize losses to competition. Further, hand weeding (twice) without herbicide tended to give greater yield than herbicide + 1 hand weeding. These results are in agreement with the findings of Dixit and Singh (1981), and support the suggestion that pendimethalin, thiobencarb, and anilofos appear to be effective in direct-seeded rice (Johnson et al 2003). As an alternative, although butachlor provides good control of grasses in wet-seeded rice, it can result in phytotoxicity in rice and its efficacy can be low in dry-seeded rice. Alternative postemergence treatments include cyhalofop-butyl at 100 g ha^{-1}, which can be effective against annual grasses, while 2,4-D at 500 g ha^{-1} at 15–30 DAS may control broadleaf weeds and sedges in wet- and dry-seeded rice.

Studies conducted at Pantnagar in on-station trials and on-farm trials indicated that *C. rotundus* may pose a severe threat to the direct-seeded rice system where regular flooding is absent. Our studies at Masodha and Kumarganj appear to confirm this. Integrated weed management practices will be necessary to control this species and will require rotation of establishment methods, herbicides, and water management regimes. Other potential threats include the grass weeds *Leptochloa chinensis* and *Ischaemum rugosum*, both of which are highly competitive (Singh et al 2003).

Sowing wheat after either zero-tillage or conventional tillage appeared to have no significant effect on grain yield at Masodha or Kumarganj in 2003-04. This finding is in contrast to findings of Yadav et al (2002), who reported higher yield with zero-tillage versus conventional tillage, and Verma et al (1991), who observed that zero-tillage gave 13% more wheat yield than conventional tillage. Dhiman and Sharma (1986) and Tripathi and Chauhan (2000) also reported higher grain yield of wheat with zero-tillage than with conventional tillage. Reasons for the disparity in results are not apparent.

Future research strategy

The following areas of research need further consideration:

1. Development of effective integrated weed management (IWM) options for dry- and wet-seeded rice.
2. Selection of competitive cultivars having rapid growth, abundant leaves, and leaf area that could compete well with weeds is needed.
3. Intercropping options of short-duration pulses and oilseeds with direct-seeded dry rice (intercrops) in order to improve profit.
4. Adaptation of agricultural implements to assist in weeding operations. These implements should be tried as an effective component of IWM in direct-seeded rice.
5. Development of cultural weed management options (sowing time, fertilizer management, and water management).
6. Gaining a better understanding of the soil seed bank and options to reduce the seed reservoir through tillage and chemicals should be developed.
7. Better understanding of weed biology and the likely weed shifts with direct-seeded rice.
8. IWM for zero-tillage wheat.
9. Improved machinery must be developed for zero-tillage, especially where stubble residues are a problem and permanent beds are kept for annual upland crop rotations. This includes equipment for mechanically controlling weeds in wheat and rice.
10. The longer-term effects of zero-tillage, particularly effects related to soil resources, residue management, and crop protection (weeds, insects, diseases, rats), must be assessed.
11. Reduced- and zero-tillage options, and complementary practices, need to be tailored and adapted to specific soils and different farmers' circumstances.

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Effect of seed rate, weed management, and establishment methods on irrigated rice in Bihar

R.K.P. Sinha, B.K.Singh, M. Kumar, A.M. Mortimer, and D.E. Johnson

Different methods of direct seeding rice were studied in field experiments on clay-loam soil at Bikramganj (Rohtas), Bihar, in the kharif seasons of 2003 and 2004. The seeding methods comprised "wet seeding" of pregerminated seed after "puddling" the soil, dry seeding after conventional dry tillage, and dry seeding after zero-tillage. In 2003, without weed control in the direct-seeded plots, rice grain yield was about half that in the transplanted plots or in the direct-seeded plots where weeds were controlled. In 2004, where weeds were not controlled in direct-seeded plots, weed competition reduced yield to zero. Where weeds were controlled, either by hand weeding or by a combination of herbicide and hand weeding, rice yield with different direct-seeding methods was similar to that of transplanting. With good weed control, mean rice yield was 5.1 t ha^{-1} in 2003 and 5.4 t ha^{-1} in 2004. In the same experiment, wheat was grown after rice and sown either after zero-tillage or after conventional tillage. Wheat yield was 18% more after conventional tillage than after zero-tillage, which may have been due to the slightly lower wheat plant stand or the greater initial weed growth after zero-tillage. Wheat yield was also greater where rice had been sown by zero-tillage rather than being transplanted.

Direct dry-seeded rice was grown on a field scale in 36 on-farm trials, over two years, and in these trials direct-seeded rice gave yield similar to that of transplanted rice. Some farmers in 2004 reported that direct-seeded rice was more resistant to drought than the transplanted crop. Different rice seeding rates for direct seeding were compared for "wet-seeded," "dry-seeded," and zero-tillage rice with seed rates of 30, 40, 60, and 75 kg ha^{-1}; all rates and establishment methods, however, gave similar grain yields.

Transplanted rice is the main *kharif* crop of Bihar and it is grown on about 3.6 million ha. It is mostly grown on medium land and lowlands, with or without irrigation. Labor costs and prices of inputs, including diesel and fertilizers, are increasing and farmers' margins are falling as a result. Further, labor is often unavailable, which causes a delay in transplanting and results in reduced grain yield. Direct seeding of rice offers a means to establish rice at a lower cost and reduces the drudgery related to some field operations. This paper presents the results of field experiments to determine the effects of weed management, establishment methods, and seed rate on direct-seeded rice.

Two field experiments were conducted at the research station at Bikramganj (Rohtas) on clay-loam soil of medium fertility, with neutral soil pH and good irrigation infrastructure.

Rice establishment method

The experiment used a split-plot design with four replications. Main-plot treatments comprised four rice establishment methods: (1) transplanting after puddling (TP), (2) wet seeding by a drum seeder after puddling (WS), (3) dry seeding by a drill after conventional tillage (DS), and (4) dry seeding by a zero-till drill after glyphosate application (ZT). The subplot treatments consisted of four levels of weed management: (1) no weed control (WC_1), (2) best-bet herbicide + hand weeding (HW) once (WC_2), (3) weed-free: best-bet herbicide + two HWs (WC_3), and (4) hand weeding twice (WC_4). In the zero-till plots (ZT), glyphosate at 1.25 kg a.i. ha^{-1} in 300 L of water was applied 10 days before sowing to kill existing weeds (mainly *Cynodon dactylon* and *Cyperus rotundus*). The rice variety grown in 2003 and 2004 was Rajendra Mashuri-1. In DS, WS, and ZT treatments, rice seed was drilled in rows 20 cm apart. The nursery beds for transplanted rice were sown on the same date as the direct-seeded treatments and seedlings were transplanted at 20 × 10-cm spacing. In DS and ZT treatments, a seed rate of 50 kg ha^{-1} was used as against 35 kg ha^{-1} in the WS. A light irrigation was applied 1 day after sowing (DAS) the DS and ZT plots to facilitate seed germination. Different herbicides were applied in WC_2 and WC_3 treatments according to the establishment method: pendimethalin at 1.0 kg a.i. ha^{-1} in 600 L of water was sprayed at 2 DAS in DS and ZT plots and anilophos at 0.4 kg a.i. ha^{-1} in 600 L of water at 8 DAS in WS plots. Hand weeding was undertaken at 28 and 56 DAS according to the treatment (WC_2 and WC_3).

Fertilizer applied to all plots consisted of 80 kg N, 37 kg P_2O_5, and 20 kg K_2O ha^{-1}. This was supplied as diammonium phosphate (DAP) at 80 kg ha^{-1} (14 kg N + 37 kg P_2O_5 ha^{-1}) and a full dose of K was applied basally and the remaining dose of N as urea was applied in two equal splits after the first and second weeding at 28 and 56 DAS. In 2003, the crop received three supplementary irrigations. Rice was sown on 6 July 2003 and harvested on 5 December 2003.

After the harvest of rice, for the *rabi* season of 2003-04, each main plot of the rice experiment (*kharif*) was divided into two equal strips. Wheat (PBW 373) was sown on 26 December 2003 either by a drill after zero-tillage or by the conventional method of seed being broadcast on unplowed land and harrowed twice followed by planking. Fertilizer was applied at a rate of 120 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1} uniformly to all plots. Wheat was irrigated at tillering, jointing, booting, and heading stages of crop growth. Weeds were controlled by an overall application of isoproturon (1.0 kg a.i. ha^{-1}) and 2,4-D (0.5 kg a.i. ha^{-1}). The wheat crop was harvested on 17 April 2004.

In kharif 2004, the trial was conducted in a strip split design and all plots and nursery beds were sown on 29 June 2004. The rice seedlings were transplanted on 2 August 2004, and the same fertilizer applications were made as in 2003. Due to failure of rains, the crop was irrigated 8 times. The harvest took place on 30 November 2004.

Rice seed rate study

The effect of differing rice seeding rates was examined in the various methods of direct seeding in kharif 2004 in an experiment with a split-plot design with three replications. The site was the

Table 1. The main effects of establishment and weed control methods on weed biomass in rice at 28 DAS (g m^{-2}), 2003.

Weed control	Weed biomass	Rice establishment	Weed biomass[a]
WC_1	23.5	TP	nd
WC_2	20.2	WS	22.9
WC_3	15.7	DS	17.6
WC_4	27.3	ZT	24.5
S.E.D.	3.13	S.E.D.	ns

[a]nd = not determined as transplanted rice not established; ns = nonsignificant.

same as for the establishment experiment. The main plots comprised three establishment methods: (1) direct seeding with dry seed after conventional dry-land preparation (DS), (2) direct seeding with pregerminated seed on puddled soil (WS), and (3) direct seeding on unplowed land after glyphosate application (ZT). The subplot treatments were four seed rates (30, 45, 60, and 75 kg ha^{-1}). Variety Rajendra Mashuri-1 was sown on 29 June 2004 in rows 20 cm apart, and DS and ZT rice plots were irrigated. Pendimethalin was applied in the DS and ZT and anilophos in the WS. 2,4-D EE (38%) at 0.5 kg a.i. ha^{-1} was sprayed 3 weeks after seeding to control *Cyperus iria* and broadleaf weeds. A further "spot hand weeding" was undertaken at 58 DAS. Fertilizer and irrigation applications were as described for the establishment method experiment (see above). The crop was harvested on 28 November 2004.

On-farm trials

Direct seeding of rice was tested in farmers' fields after farmers either attended field days or visited researcher-managed trials. Farmers involved with direct seeding in on-farm trials were supported with technical advice and a loan of machinery. Plot size ranged from 0.1 to 0.25 ha and was commonly half a single field being direct seeded and the other transplanted. Crop establishment methods for the direct-seeded plots were as described above for the establishment experiment (see above).

Results

Rice establishment method

Weed growth. In 2003, at 28 DAS, there was less total weed biomass in the plots that had received herbicide than where hand weeding alone was undertaken (Table 1). There were no differences among the direct-seeding methods. *C. dactylon* and *Ludwigia hyssopifolia* were the dominant weed species in the direct-seeded treatments (Table 2), whereas other species included *Cyperus* spp., *Ischaemum rugosum, L. adscendens, Ammania baccifera, Echinochloa crus-galli, Marsilea minuta, Monochoria vaginalis, E. colona, Fimbristylis* sp., *Commelina diffusa*, and *Dactyloctenium aegyptium.*

By 2004, weed growth increased considerably though as in 2003 there were no differences between direct-seeding methods. Herbicides reduced weed growth compared with hand weeding alone (Table 3).

Initial plant stand and panicle density. There were no significant effects of establishment method or weed control treatment on rice plant population densities at 28 DAS in the direct-seeded

Table 2. The composition (% of total weed biomass) of weed species in direct-seeded rice at 28 DAS, 2003.

Rice establishment	Weed species			
	Cynodon dactylon	*Cyperus iria*	*Ludwigia hyssopifolia*	Other
Wet seeding	44	3	48	5
Dry seeding	30	9	47	14
Zero-tillage	40	6	51	3

Table 3. The main effects of establishment and weed control methods on weed biomass in rice at 28 DAS (g m^{-2}), 2004.

Weed control	Weed biomass	Rice establishment	Weed biomass[a]
WC_1	159.0	TP	n.d
WC_2	69.1	WS	106.6
WC_3	57.1	DS	112.7
WC_4	118.0	ZT	83.0
S.E.D.	15.6	S.E.D.	25.3

[a]n.d. = not determined as transplanted rice not established; n.s. = nonsignificant.

rice (WS, DS, ZR). Mean rice plant population density was 105 plants m^{-2}. The main effects of establishment show that the transplanted plots had the highest panicle density and there were no significant differences between the direct-seeded treatments. In the plots with no weed control (WC_1), rice panicle density with direct seeding was approximately half that of the transplanted plots (Table 4).

Rice grain yield. In 2003, with no weed control (WC_1) in the direct-seeded plots, competition from weeds reduced rice yield to approximately half that of the transplanted plots (Table 5). Further, comparing yields within a given direct-seeding method, rice yields with no weed control were about half those where weeds were controlled. Where weed control was undertaken in WC_2, transplanting gave a higher yield than DS, whereas in other treatments yields did not differ significantly. In 2004, the second year of the study, with no weed control (WC_1), the direct-seeded rice produced no yield (Table 6) because of the effects of weed competition. Where weeds were controlled, the yields were similar, with the exception of the hand-weeded plots (WC_4) in transplanted rice that produced a greater yield than those in ZT.

Wheat grain yield. There was 18% more wheat grain yield where wheat had been established by conventional tillage rather than by zero-tillage (Table 7). This yield difference may have been partly due to the larger initial plant stand under conventional tillage (146 vs. 138 plants m^{-2}, S.E.D. = 1.6) or to the greater initial weed growth as measured at 30 DAS (3.9 vs. 5.6 g m^{-2}, S.E.D. = 0.48). *Phalaris minor* was one of the major weeds in the wheat crop but the plant density of this species, recorded at 30 DAS, did not differ significantly between rice and wheat establishment

Table 4. The effects of establishment and weed control on the number of rice panicles at harvest, 2003 (panicles m^{-2}).[a]

Rice establishment	Weed control				Mean
	WC_1	WC_2	WC_3	WC_4	
Transplanting	351	360	366	355	358
Wet seeding	174	293	315	313	274
Dry seeding	159	320	355	324	289
Zero-tillage	166	344	348	337	299
Mean	213	329	346	332	

[a]S.E.D. for comparing main effects of establishment = 5.1, weed control = 9.7, and establishment × weed control = 17.5.

Table 5. Grain yield of rice (t ha^{-1}) as influenced by method of establishment and weed management interaction, kharif 2003.[a]

Rice establishment	Weed control				Mean
	WC_1	WC_2	WC_3	WC_4	
Transplanting	4.97	5.45	5.17	5.24	5.20
Wet seeding	2.73	4.77	5.00	4.57	4.27
Dry seeding	2.16	4.35	5.18	5.03	4.18
Zero-tillage	2.45	4.70	4.99	4.47	4.15
Mean	3.08	4.82	5.09	4.82	

[a]S.E.D. for comparing main effects of establishment = 0.184, weed control = 0.219, and establishment × weed control = 0.422.

Table 6. Grain yield of rice (t ha^{-1}) as influenced by stand establishment and weed management interaction, kharif 2004.[a]

Rice establishment	Weed control				Mean
	WC_1	WC_2	WC_3	WC_4	
Transplanting	5.62	5.70	5.63	5.96	5.73
Wet seeding	0.0	5.21	5.25	5.46	3.98
Dry seeding	0.0	5.65	5.35	5.58	4.14
Zero-tillage	0.0	5.51	5.48	5.00	4.00
Mean	1.41	5.52	5.42	5.50	

[a]S.E.D. for comparing main effects of establishment = 0.171, weed control = 0.155, and establishment × weed control = 0.318.

Table 7. Effect of rice and wheat establishment method on wheat grain yield (t ha^{-1}), 2003-04.[a]

Rice establishment method	Wheat establishment		
	Conventional tillage	Zero-tillage	Mean
Transplanting	2.33	1.94	2.13
Wet seeding	2.53	2.12	2.37
Dry seeding	2.54	2.08	2.31
Zero-tillage	2.71	2.31	2.51
Mean	2.53	2.14	

[a]S.E.D. for comparing main effects of rice establishment = 0.111, wheat establishment = 0.042, and establishment × weed control = 0.126 (nonsignificant).

Table 8. Rice grain yield (t ha^{-1}) in on-farm trials following different establishment methods.

Item	2003	2004
Number of farms	13	23
Dry-seeded rice	4.22	4.44
Transplanted rice	4.65	4.09[a]
S.E.D.	0.35	0.20

[a]Includes two farms where transplanted rice failed because of drought.

methods. There were significant effects of the preceding rice establishment method, with the main effect of zero-tillage in rice resulting in the highest wheat yield (2.51 t ha^{-1}) and where rice was transplanted the lowest (2.13 t ha^{-1}). Wheat yields were greatest where rice was sown by zero-tillage and wheat by conventional tillage (2.71 t ha^{-1}).

On-farm trials

The yields from on-farm trials are shown in Table 8. Yields from transplanted rice were slightly greater than for direct-seeded rice in 2003 and slightly less in 2004; however, the differences were not significant in both years. Farmers reported that direct-seeded fields were less susceptible to moisture stress and, for those with the infrastructure, required less irrigation to maintain than transplanted fields. On two farms, both direct-seeded and transplanted rice crops failed.

The most important weeds in farmers' fields were *Trianthema monogyna*, *C. iria*, and *E. colona*. Pendimethalin (at 1.0 kg a.i. ha^{-1}) was particularly effective in controlling *E. colona* in dry-seeded rice when applied 2 days after seeding and where the soil was moist after the field had been irrigated. Application of 2,4-D EE (38%) at 0.5 kg a.i. ha^{-1} at 21 DAS controlled *C. iria* and *T. monogyna* and other broadleaf weeds.

Rice establishment method and seed rate. The different seed rates between 30 and 75 kg ha^{-1} or whether the crop was sown wet seeded, dry seeded, or after zero-tillage had no significant

Table 9. The effects of rice establishment and seed rate on rice grain yield (t ha^{-1}), kharif 2004.[a]

Seed rate (kg ha^{-1})	Method of stand establishment			
	Dry seeding	Wet seeding	Zero-tillage	Mean
30	5.01	4.74	4.85	4.87
45	4.77	4.83	4.74	4.78
60	4.66	5.10	4.59	4.78
75	4.53	5.28	4.55	4.79
Mean	4.58	4.99	4.68	4.80

[a]S.E.D. for establishment method = 0.118 (ns), seed rate = 0.153 (ns), establishment method × seed rate = 0.258 (ns). ns = nonsignificant.

effect on grain yield (Table 9). Grain yield ranged from 5.28 t ha^{-1} with a 75 kg ha^{-1} seed rate in wet-seeded plots to 4.53 t ha^{-1} with 75 kg ha^{-1} seed in dry-seeded plots.

Conclusions

The results of the studies over two years show direct seeding as a feasible alternative to transplanting providing weeds are adequately controlled. With hand weeding alone or with the use of herbicides, yield from direct-seeded rice was similar to that from transplanting. The threat that weeds pose to direct-seeded crops appeared to increase between the first and second year of direct seeding, which may be due to an increase in weed growth and a shift in weed species, which have been demonstrated elsewhere in the Indo-Gangetic Plains (see V.P. Singh et al, this volume). The results also show that wet seeding with pregerminated seed and dry seeding after conventional or zero-tillage gave similar yield as did seeding rates of between 30 and 75 kg ha^{-1} with these establishment methods. In practice, the choice of direct-seeding method may be limited by farmers' access to machinery (e.g., zero-till drill) or the weather, such as an early heavy onset of monsoon rains, which would make dry seeding problematic. The choice of seeding rate may depend largely on the quality of land leveling and water control as it is presumed that the better the field/seedbed conditions, the lower the seed rate can be without incurring a yield penalty. Poor land leveling, water control, or seedbed conditions may require more seeds to achieve the desired rice plant population.

Wheat sown after conventional tillage gave an 18% better yield than wheat sown by zero-tillage. Further, where the preceding rice crop had been sown by zero-tillage, the subsequent wheat crop appeared to impart a beneficial effect as yield was significantly greater than wheat yield where the previous rice crop had been transplanted. This effect did not appear to be due to the absence of puddling for the preceding rice crop as where rice had been puddled prior to wet seeding, the yield in wheat was not different from where the land had been dry cultivated and the rice dry seeded.

In 2004, the distribution of monsoon rains was unfavorable for many farmers, with long periods of drought around transplanting time. Large areas in Bihar remained unplanted in 2004 at the same time as nurseries were full with rice seedlings. Farmers who were dry direct seeding rice had an advantage under these conditions as they did not require fields to be flooded to prepare the land and transplant the rice.

Although the feasibility of direct seeding was demonstrated over a two-year period, these studies need to be assessed together with data on labor and water use, the relative risks related to direct seeding, and information requirements of farmers to enable them to adopt these options. Gathering this information requires additional participative studies in Bihar.

Notes

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Weed management

Integrated weed management in direct-seeded rice

Govindra Singh

Transplanting rice seedlings on puddled soils is widespread in the irrigated ecosystem of the Indo-Gangetic Plains. Puddling, a process of wet tillage of soil in excessive water, requires a large volume of water, breaks soil aggregates, reduces water percolation rate during the cropping season, and suppresses weeds. However, puddling also results in poor soil physical conditions for establishing and raising succeeding crops. The shortage and rising cost of labor and excess water use in puddling are major constraints prompting alternatives to transplanting irrigated rice. Traditionally, direct seeding of rice in India has been largely practiced in low-productivity systems common to rainfed areas. However, it has largely replaced transplanted irrigated rice in Southeast Asia, particularly in the Philippines, Malaysia, and Thailand. Direct seeding in irrigated rice offers the advantages of faster and easier planting, reduced labor, earlier crop maturity by 7–10 days, more efficient water use and higher tolerance of water deficit, and lower methane emission, and it also eliminates operations related to nursery preparation for transplanting. Whether rice is direct-seeded onto a dry or wet seedbed and seed is pregerminated or dry, rice seedling growth is accompanied by simultaneous emergence of weeds (grasses, broadleaf weeds, and sedges) because of the absence of flooding during early stages. Weed abundance in the crop is usually higher in dry direct-seeded culture than in wet direct-seeded and transplanted rice cultures mainly because of differences in land preparation at the time of establishment. Integration of weed control practices is essential for direct-seeded rice and places emphasis on clean seedbeds at land preparation and early preemergence chemical weed control, followed by manual weeding 30–40 days after seeding. This paper discusses the various methods that can be integrated in relation to the major weeds of direct-seeded rice.

Rice in the Indo-Gangetic Plains is managed by two principal culture methods—transplanting and direct seeding. Transplanting rice seedlings on puddled soils is widespread in the irrigated ecosystem. Puddling, a process of wet tillage of soil in excessive water, requires a high amount of water, breaks soil aggregates, reduces the water percolation rate, and suppresses weeds. Puddled soil becomes hard after drying, leading to the development of cracks and thereafter the water requirement increases manyfold because of deep percolation through cracks. Puddling also results in poor soil physical conditions for establishing and raising succeeding crops (Tripathi et al 2003). The shortage and rising cost of labor and excess water use in puddling are the incentives to seek alternatives to transplanting, such as direct seeding. This has already largely replaced transplanted irrigated rice in Southeast Asia, particularly in the Philippines, Malaysia, and Thailand (Pandey and Velasco 2002). In India, direct seeding of rice is largely a low-productivity system more common in rainfed areas. Direct seeding offers such advantages as faster and easier planting, reduced labor and drudgery, earlier crop maturity by 7–10 days, more efficient water use and higher tolerance of water deficit, fewer methane emissions, and often higher profit in areas with an assured water supply (Balasubramanian and Hill 2002). Direct seeding also eliminates the use of seedlings and related operations such as seeding, nursery preparation, care of seedlings, pulling, bundling, transporting, and transplanting (Serrano 1975). In direct-seeded rice culture, weeds are the biggest constraint; because of the absence of flooding during early stages, all types of weeds such as grasses, nongrasses, and sedges emerge simultaneously at high density with rice seedlings.

Rice is direct-seeded as dry or wet, based on the soil physical conditions of the seedbed and seed (pregerminated or dry). The weed presence is higher in dry direct-seeded culture than in wet direct-seeded and transplanted rice cultures mainly because of differences in land preparation. The use of only one method of weed control in a direct-seeded rice crop may not be successful for raising a good crop. Various methods such as cultural practices and manual, mechanical, and chemical methods should be carried out together.

Weed species associations

Weed flora in direct-seeded rice consists of various kinds of grasses, nongrasses (broadleaf), and sedges. The community composition of these weeds varies according to crop establishment methods (Mabbayad et al 1983, Sarkar and Moody 1983), cultural methods (Bernasor and De Datta 1983, Mabbayad et al 1983), crop rotation, water and soil management (Bhan 1983), location (Janiya and Moody 1983, Moorthy and Saha 2001), weed control measures (De Datta 1977, Noda 1977, Janiya and Moody 1989), climatic conditions, and the inherent weed flora in the area. The weeds of economic importance associated with direct-seeded rice have been described by Smith (1983), Noda (1977), Gupta and O' Toole (1986), Moody (1989), Singh et al (1987), and Johnson (1996). The most common weeds occurring in direct-seeded rice in India are listed in Table 1.

Echinochloa colona and *E. crus-galli* are the most serious weeds affecting direct-seeded rice. *E. colona* requires less moisture than *E. crus-galli*. The density of these weeds in direct-seeded rice will depend on moisture conditions in the field. *Cyperus rotundus* and *Cynodon dactylon* may be major problems in upland conditions, particularly in poorly managed fields. The other weeds of major concern in direct-seeded rice are *Paspalum* spp., *Ischaemum rugosum, Leptochloa chinensis, Digitaria sanguinalis, Dactyloctenium aegyptium, Commelina* spp., *Caesulia axillaris, Cyperus iria, Fimbristylis miliacea,* and *Cyperus difformis.*

In direct-seeded rice during the first 30 days after sowing, nongrassy weeds (broadleaf) dominated the grassy weeds and sedges, constituting more than 62% of the total weed population where *Trianthema monogyna* alone contributed more than 50% and 60% at 15 and 30 d after sowing, respectively (Table 2). At later stages, grasses dominated over nongrasses and sedges, constituting more than 90% of the total weed population at 75 d after sowing, at which *Echinochloa colona* alone contributed more than 80% of the total weed population at 60 d after sowing and beyond.

Studies conducted at Pantnagar in station trials and on-farm trials indicated that *Cyperus rotundus* may pose a severe threat to the direct-seeded rice system where regular flooding is absent.

Table 1. List of common weed species in direct-seeded rice.[a]

Weed species	Family	Habitat	Importance
Alternanthera sessilis (L.) R. Br. ex Roem. & Schult.	Amaranthaceae	A	c
Amaranthus viridis L.	Amaranthaceae	A	c
Ammannia baccifera L.	Lythraceae	A	c
Brachiaria ramosa (L.) Stapf	Poaceae	A	c
Caesulia axillaris Roxb.	Asteraceae	A	b
Celosia argentea L.	Amaranthaceae	A	c
Cleome viscosa L.	Capparaceae	A	c
Commelina benghalensis L.	Commelinaceae	A	b
C. communis	Commelinaceae	A	c
Corchorus acutangulus	Tiliaceae	A	c
Cyanotis axillaris	Commelinaceae	A	c
Cynodon dactylon (L.) Pers.	Poaceae	P	c
Cyperus brevifolius (Rottb.) Hassk.	Cyperaceae	A	c
C. difformis L.	Cyperaceae	A	b
C. iria L.	Cyperaceae	A	b
C. rotundus L.	Cyperaceae	P	c
Dactyloctenium aegyptium (L.) Willd.	Poaceae	A	a
Digera arvensis	Amaranthaceae	A	c
Digitaria ciliaris (Retz.) Koel.	Poaceae	A	a
D. sanguinalis (L.) Scop.	Poaceae	A	a
Echinochloa colona (L.) Link	Poaceae	A	a
E. crus-galli (L.) P. Beauv.	Poaceae	A	a
Eleusine indica (L.) Gaertn.	Poaceae	A	a
Fimbristylis miliacea (L.) Vahl	Cyperaceae	A	b
Leptochloa chinensis (L.) Nees	Poaceae	A	a
Oxalis latifolia Kunth	Oxalidaceae	P	c
Panicum maximum Jacq.	Poaceae	A	c
Paspalum distichum L.	Poaceae	A	c

[a]a = very important, b = moderately important, c = less important, A = annual, B = biennial, P = perennial.

Integrated weed management practices will be necessary to control this species and will require rotation of establishment methods, herbicides, and water management regimes. Other potential threats are the grassweeds *Leptochloa chinensis* and *Ischaemum rugosum*, both of which are highly competitive (Singh et al 2003).

Losses and critical duration of weed-crop competition

Weeds in direct-seeded rice adversely affect the yield, quality, and cost of production as a result of competition for various growth factors. The extent of loss varies depending upon cultural methods, rice cultivars, weed species associated, and their density and duration of competition. The yield loss may vary from 10% to complete failure of the crop depending upon the situation. In general, the potential yield loss from weeds is less in wet-seeded rice than in dry-seeded rice (Fig. 1). In a survey of upland rice-producing countries covering 80% of the total production area, weeds were the most widely reported biological constraint to yield (Johnson 1996). In West Africa, yields of upland rice with farmers' weed control were 44% lower than on weeded researcher plots. Losses

Table 2. Percentage composition of grassy weeds, nongrassy weeds, and sedges and their contribution (%) to dry matter production of weeds at different stages (average of three crop seasons in unweeded plots).

Stages (DAS)[a]	Grassy weeds		Nongrassy weeds		Sedges	
	Population	Dry matter	Population	Dry matter	Population	Dry matter
15	30.0	25.2	60.0	72.6	10.0	2.2
30	29.2	11.0	62.6	88.4	8.2	0.6
45	54.0	88.9	15.4	8.7	30.6	2.4
60	85.2	98.7	0.0	0.0	14.8	1.3
75	90.8	99.5	0.0	0.0	9.2	0.5

[a]DAS = days after sowing.

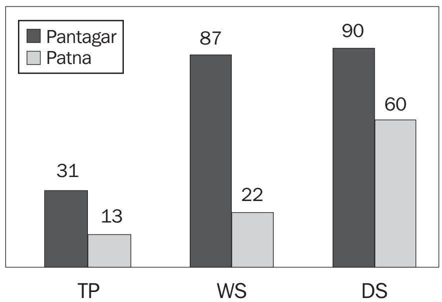

Fig. 1. Potential yield loss (%) caused by weeds in rice cultures. TP = transplanted rice, WS = wet-seeded rice, DS = dry-seeded rice.

caused by uncontrolled weeds in India were up to 90% and, in both lowland and upland systems in Africa, losses were 28–100%. Losses can be severe in direct-seeded rice as the rice and weed seedlings are at similar growth stages. The competitive advantage of transplanted rice is due to the size difference between 4–5-week-old seedlings (20–30 cm tall) and the weeds that emerge later, and immediate flooding after transplanting limits weed establishment. This results in less yield losses from weed competition in transplanted rice than in direct-seeded rice. In Asia, yield losses caused by uncontrolled weeds in direct-seeded lowland rice were reported to be 45–75% and for transplanted lowland rice approximately 50%. Every farmer adopts some weed control measures and therefore losses in farmers' fields are likely to be considerably less. To formulate an effective and economical weed management system for direct-seeded rice, it is essential to establish a critical duration of weed-crop competition and a limit for an acceptable presence of weeds.

The yield decrease in direct-seeded rice increases with the increase in competition duration during the initial period. But, at later stages or after a certain stage, the rate of decrease may not change because maximum damage has already occurred. Infestation of *Echinochloa colona, Dactyloctenium aegyptium, Cyperus iria, C. rotundus,* and *Trianthema monogyna,* with a total density of 381 m^{-2} and dry matter production of 531.2 g m^{-2}, resulted in a grain yield loss of direct-seeded rice of more than 96% (Singh et al 1987). The higher rate of dry matter production by weeds was

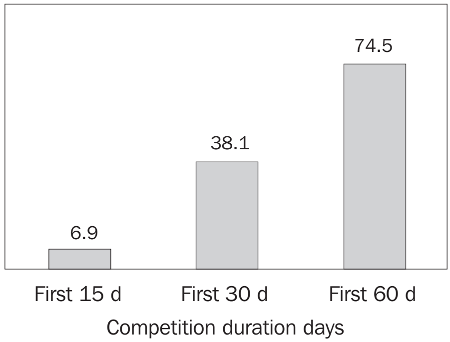

Fig. 2. Yield loss (%) caused by weed-crop competition up to given dates in dry-seeded rice.

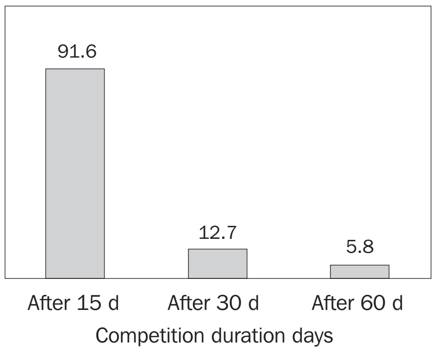

Fig. 3. Yield loss (%) caused by weed-crop competition after given dates in dry-seeded rice.

during 15–30 d after seeding. The rate of dry matter production by weeds varies according to their emergence and life cycle.

Trianthema monogyna was found to grow faster than other weed species during early stages because of its shorter life cycle and it contributed much more to competition with the rice crop than other weed species such as *Echinochloa colona* during the first 4–5 weeks. The effective period of competition occurred in two phases: between 15 and 30 d, and 45 and 60 d after seeding. The competition in direct-seeded rice beyond 15 d after seeding may cause a significant reduction in grain yield. However, competition for the first 15 d only may not have much adverse effect on the crop (Figs. 2 and 3).

A weedy situation for the first 15 d only or weed-free situation for the first 60 or 75 d produced grain yields comparable with weed-free conditions until harvesting (Table 3).

It is important to minimize weed-crop competition in direct-seeded rice during the early stages of the crop before it forms a closed leaf canopy. In direct-seeded rice, this critical duration is 15–45 or 15–60 d after seeding (Fig. 4). Competition with weeds during this period causes irreversible damage to the crop.

Table 3. Grain yield of rice (kg ha^{-1}) as affected by crop-weed competition.

Treatment	Season I	Season II	Season III	Mean	Losses to yield (%)
Weedy for the first					
15 DAS[a]	4,352	5,305	4,782	4,873	(–) 6.9
30 DAS	4,016	2,386	3,314	3,239	(–) 38.1
45 DAS	3,143	2,045	2,945	2,711	(–) 48.2
60 DAS	2,114	102	1,782	1,333	(–) 74.5
75 DAS	229	80	451	253	(–) 95.2
Up to harvest	225	45	306	192	(–) 96.3
Weed-free for the first					
15 DAS	668	68	576	437	(–) 91.6
30 DAS	3,529	193	2,567	2,096	(–) 60.0
45 DAS	4,715	4,544	4,452	4,570	(–) 12.7
60 DAS	4,824	5,305	4,677	4,935	(–) 5.8
75 DAS	5,100	5,907	5,025	5,344	(+) 2.0
Up to harvest	5,008	5,532	5,172	5,237	–
LSD (P = 0.05)	561	575	498	–	–

[a]DAS = days after rice seeding.

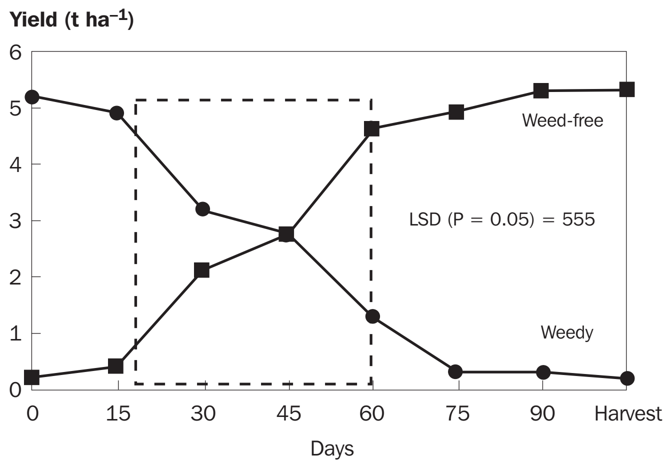

Fig. 4. Critical duration of weed-crop competition in dry-seeded rice.

Weed management in direct-seeded rice can be accomplished by various cultural, mechanical, and herbicide practices. Cultivation of rice fields before seeding, especially during the summer months, helps in reducing perennial weeds such as *Cyperus rotundus* and *Cynodon dactylon*. A properly prepared field with good leveling provides a favorable medium for optimum crop establishment and plant growth. It also helps in uniform emergence of weeds. If a majority of weeds emerge at one time, the efficacy of herbicides used in such fields increases.

It may be possible to limit weeds in direct-seeded rice by adopting the stale seedbed technique in which the seedbed may be prepared at least 7–10 d in advance of seeding with moisture ensured either by irrigation or rain to stimulate germination and emergence of weeds, which are then destroyed either by shallow cultivation or the use of herbicides such as paraquat or glyphosate. The use of herbicides may have the advantage of destroying weeds without disturbing the soil, thus reducing the possibilities of bringing new seeds to the upper soil surface. Rice should be sown with a minimum soil disturbance after destroying the emerged weeds. The use of zero-till ferti-seed drills may be quite useful for this purpose. A reduction of 59% in the density of *Echinochloa colona* and 78% reduction in fresh weed weight were recorded from the stale seedbed technique in the Philippines (Moody 1982). Research on this aspect is limited.

Prevention of the introduction of new weed species should be a prerequisite for any approach to weed management. Rice seed contaminated with weed seeds may introduce a new species to a given field or add to an existing weed population. Preventing weeds from entering an area may be easier than trying to control them once they have established. Noncomposted manure can have weed seeds and higher levels of available nitrogen that stimulate the germination of weeds. Animals fed weed-infested fodder, straw, and grains result in a large percentage of the weed seeds passing through the digestive tract with undestroyed viability. During proper composting of such manure, the heating process destroys weed seed viability.

The competition offered by a crop can affect the degree of weed control achieved by herbicides. Crop density changes the parameters and quality of environment available for the growth of weeds in association with the crop. In low crop plant populations resulting from low seed rate, faulty germination, uneven seeding, or damage to crop seedlings, weed growth is profuse, leading to intense weed-crop competition. Increasing seed rates for direct-seeded rice has little influence on weed suppression, probably because of the intense weed pressure (Moody 1982). An increase in grain yields of rice varying with the increase in seed rate from 60 to 140 kg ha^{-1} without weed control was recorded at IRRI, Philippines (1964). But, herbicide use resulted in higher grain yields at 100 kg seed ha^{-1} than at 140 kg ha^{-1}. Good rice stands are more competitive with *Echinochloa* spp. than poor stands. A stand of 10.8 plants m^{-2} of *E. crus-galli* in a rice stand of 32.4 plants m^{-2} reduced yields by 57%, but the same stand of *E. crus-galli* in a rice stand of 334.8 plants m^{-2} reduced yields by 27% only. Seed rates of 150 and 200 kg ha^{-1} significantly reduced the dry matter production of weeds compared with 100 kg seed ha^{-1}, but seed rates had no effect on the weed population (Deka 1983). However, 100 kg seed ha^{-1} with two manual weedings provided better yield than higher seed rates. Too thick a stand should be avoided because it tends to increase lodging, prevents the full benefit of nitrogen application (Anon 1986), and increases the chances of rat damage (Castin and Moody 1989). The use of higher seed rates may increase input cost and weaken seedling vigor, reduce tillering and increase the proportion of infertile tillers, cause N deficiency, and enhance the incidence of diseases and pests.

Rice varieties with weed-suppressing characters are an important aspect in managing weeds in direct-seeded rice. Tall, fast-growing traditional rice varieties were more competitive with weeds than dwarf high-yielding varieties (Kawano et al 1974). The competitive ability of different rice varieties has become a focus of research, with the intention of combining competitive ability with other desirable characters. Plant characters that increase the size and vegetative vigor of rice plants in the early growth stages enhance competitive ability. Such factors include tillering capacity, spreading growth habit, height, leaf canopy, and root development. Genetic variations in rice varieties exist with respect to competitive ability against weeds. The African rice *Oryza glaberrima* is a source of a number of these traits that confer competitive ability with weeds, and to produce rice plant types. Javanica type *O. sativa*, *O. glaberrima,* and wild rice have been suggested as possible

Table 4. Crop-weed competition index (WI) of rice varieties under dry-seeded rice culture with one weeding 28 days after seeding.

WI range	Varieties
3.3–4.8	Pant Dhan-6, UPRI-1230-9-2, UPRI-93-63-2, IET-16840, IET-16843, Pusa 44, Narendra-359
6.1–8.5	UPRI-95-49, UPRI-92-97, UPRI-1561-6-3, Manhar
9.5–11.5	IET-16615, WITA-7, WITA-3
15.7–18.6	Govind, Nidhi, WITA-4
Negligible	IET-16613, IR64, Aditya

sources of allelopathic effects, which could be transferred into commercial rice cultivars (Johnson 1996, Ahmed and Bhyiyan 2004). Studies on crop-weed competition of rice varieties under direct-seeded rice culture with one weeding done at the 4-wk stage revealed that there was a negligible crop-weed competition index (WI) for rice cultivars IET-16613, IR64, and Aditya, whereas it was 3.3–4.8 for rice cultivars Pant Dhan-6, UPRI-1230-9-2, UPRI-93-63-2, IET-16840, IET-16843, Pusa 44, and Narendra-359. A higher WI of 9.5–11.5 was recorded for rice cultivars IET-16615, WITA-7, and WITA-3 (Table 4).

The effect of soil moisture and water depth in rice on weed emergence and suppression has long been recognized (De Datta et al 1973, De Datta 1988). Weed density with standing water in the early stages may be reduced but, once the weeds are established, their stand is not affected. The response of weed species to soil moisture levels and depth of standing water is variable (Johnson et al 2004). In deep water, *Monochoria vaginalis* was predominant, whereas, in saturated soil (with standing water), *Echinochloa* spp. and *Fimbristylis miliacea* have been found to be dominant. Herbicide efficacy is also affected by soil moisture. Pendimethalin when applied as preemergence in dry-seeded rice performs effectively when enough soil moisture is available in the upper surface.

Manual weeding

Manual weeding is the most prevalent practice of weed control in direct-seeded rice in India. It has been described as slow and laborious, less effective on some occasions because of escape or regeneration of perennial weeds, having many flushes of weeds, and impractical during adverse weather conditions. Repeated weeding is generally required. Labor for timely weeding is expensive and often unavailable. Delayed weeding results in crop loss and increased cost. The frequency of manual weeding will depend on the weed species and its density and emergence pattern. Depending on these factors, normally 2–3 manual weedings at appropriate stages have been found to be effective for a desired level of weed control in direct-seeded rice. The first weeding should be done at 20–25 DAS in dry-seeded rice and at 25–30 DAS in wet-seeded rice, followed by a second weeding at 45–50 DAS. Further weedings will depend on the actual field conditions. Under high-rainfall situations, three weedings at 15, 30, and 60 d after seeding produced grain yields on a par with a crop kept free from weeds throughout the season. Two weedings done either 15 and 30 or 15 and 60 d after seeding provided lower grain yield (Fig. 5).

The delay in first weeding increased the person-days required for weeding operations. Single weeding at 30, 45, and 60 d after seeding required 115, 120, and 127 person-days per ha, whereas two weedings done at 15 and 30 d or 15 and 45 d required only 88 and 86 person-days, respectively. However, two weedings done at 30 and 60 d required 152 person-days per ha (Fig. 6). The increase in person-days with a delay in weeding was due to increased weed biomass.

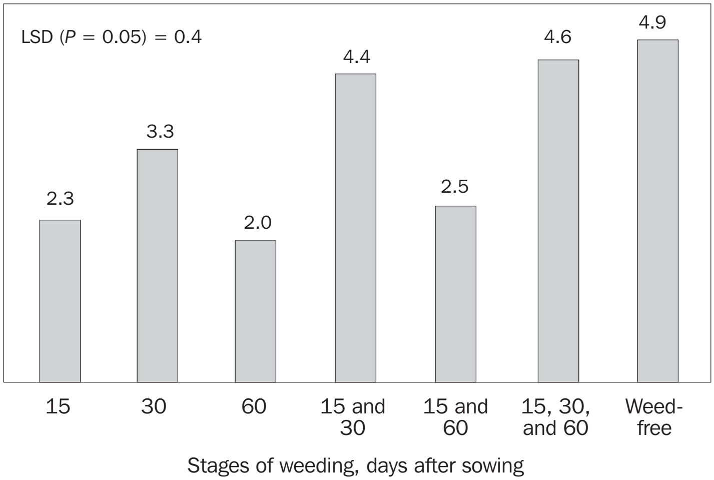

Fig. 5. Effect of weeding on grain yield (t ha^{-1}) of direct-seeded rice.

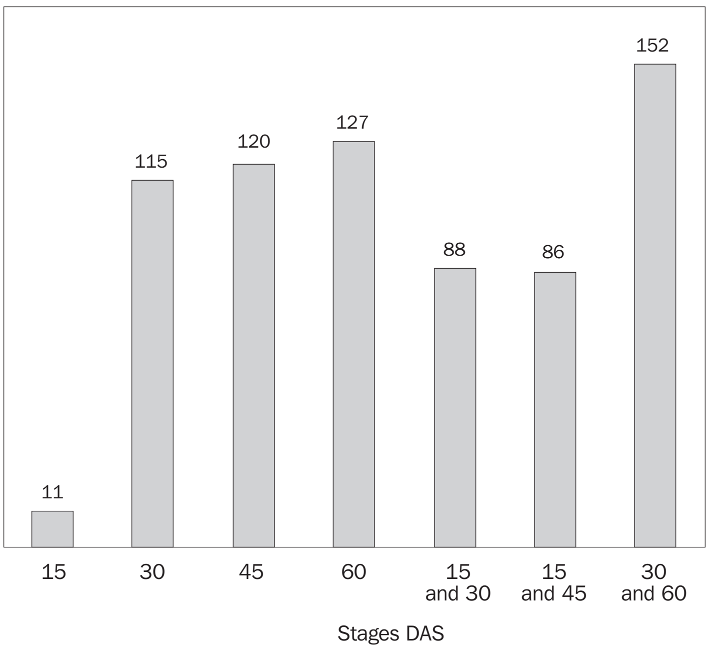

Fig. 6. Person-days required for weeding at various stages of dry-seeded rice.

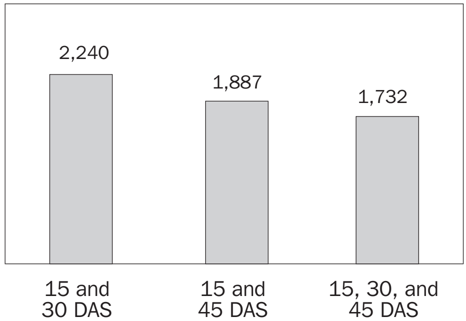

Fig. 7. Net returns (Rs. ha^{-1}) because of weeding frequency in direct-seeded rice.

Table 5. Herbicides evaluated for direct-seeded rice.

Anilofos	Fenoxaprop
Butachlor	Imazosulfuron
Bentazon	Oxadiazon
Cinmethylin	Oxyfluorfen
Clefoxydim	Pendimethalin
Cinosulfuron	Pretilachlor
Cyhalofop	Propanil
Dithiopyr	Quinclorac
Ethoxy-sulfuron	Thiobencarb
Almix	2,4-D

Two weedings done at either 15 and 30 or 15 and 45 DAS provided higher net returns (Fig. 7).

Herbicides

The herbicides tested and available for direct-seeded rice have a narrow weed control spectrum and low efficacy when used alone and do not provide season-long weed control. A list of herbicides widely tested in India appears in Table 5.

Pendimethalin, thiobencarb, and anilofos have been found more effective and safer for direct-seeded rice. Pendimethalin at 1.0 kg ha^{-1} as preemergence has been quite effective and economical for dry-seeded rice (Jayadeva and Bhairappanavar 2002, Singh et al 2002). But good surface moisture is essential for its better efficacy. Anilofos at 400 g ha^{-1} and thiobencarb at 1.0 kg ha^{-1} as early postemergence have proved better and safer in wet-seeded rice than others (Bindra et al 2002, Jena et al 2002, Moorthy and Saha 2002, Saha et al 2003). Butachlor provides good control of grasses in wet-seeded rice but it has been phytotoxic to rice seedlings without safener (Bindra et al 2002, Jayadeva and Bhairapanavar 2002, Saha et al 2003). Its efficacy is quite low under dry-seeded rice culture. Cyhalofop-butyl at 100 g ha^{-1} as postemergence has also been found very effective against most of the annual grasses in wet-seeded rice (Angiras and Attri 2002, Chaubey et al 2001, Saini 2003). The use of 2,4-D at 500 g ha^{-1} at 30–35 DAS provides effective control of nongrasses and sedges in wet- and dry-seeded rice. Ethoxy-sulfuron has been found to provide effective control of broadleaf weeds and some sedges and is compatible with anilofos, which thus widens the weed control spectrum (Bindra et al 2002, Moorthy and Saha 2002a,b, Saha et al 2003). By using these herbicides and manual weeding in direct-seeded crops, integrated weed management systems have been developed (Johnson et al 2003).

Integrated management

Integrated weed management (IWM) is an approach in which principles, practices, methods, materials, and strategies are chosen to control weeds while minimizing undesirable results. It includes the use of multiple-pest-resistant, high-yielding, well-adapted varieties that resist weed competition; precision placement of fertilizers to give the crop a differential advantage in competing with weeds; timing the fertilizer application for maximum stimulation of the crop and minimum stimulation of the weed population; preplanting seedbed tillage; effective seedbed preparation; seeding methods that enhance crop growth and minimize weed growth; optimum plant populations per hectare, including close spacing in rows and close spacing between rows to optimize crop growth and minimize weed growth; the use of crops that form a canopy for shading as early in the growth season as possible to discourage weed growth; the use of judicious irrigation practices; timely and appropriate cultivation; sound crop rotations; crop diversification; field sanitation; the use of clean crop seeds; harvesting methods that do not spread weed seeds; the use of biological agents (insects and pathogens); and effective chemical methods.

Each weed management component described above has its own merits and disadvantages. Therefore, a combination of two or more weeding methods must be evaluated for widening the weed control spectrum and efficacy in order to achieve effective and economical weed management in direct-seeded rice. The sequential application of preemergence herbicides such as pendimethalin in dry-seeded rice or early postemergence application of anilofos/thiobencarb for the control of annual grasses in wet-seeded rice and postemergence application of 2,4-D against sedges and nongrassy weeds in wet- and dry-seeded rice may be a better option than the use of one herbicide. The postemergence herbicides can be substituted with manual weeding, which may have an added advantage of controlling escapes and reducing herbicide load. This will also help in managing herbicide-resistant biotypes. In addition to this, cultural practices favoring early crop establishment in a weed-free environment and discouraging weed growth should be an integral part of this system. Figure 8 shows a conceptual model of integrated weed control in rice (Noda 1977).

Any single method used in isolation cannot provide effective and season-long weed control because of variations in the growth habit and life cycle of weeds. When integrating various methods, the objective should be to control all those species that may cause an economic loss to the crop. Herbicide use moves the agroecosystem to low species diversity, with new problem weeds appearing, so there is a need for an ecological approach to weed control rather than relying totally on chemical control methods (Moody 1992). Weeds of secondary importance may emerge as a primary weed problem because of the continuous use of a single herbicide or herbicides with a similar mode of action. This problem can be avoided by adopting an integrated approach, including herbicide rotation, herbicide combinations, and crop rotation. Le (1990) advocated the alternative usage of herbicides with different grass control spectra over seasons to prevent the emergence of tolerant weeds. Some of the herbicide combinations or their sequential application may widen the weed control spectrum with better efficacy. Follow-up application of 2,4-D and Almix (a ready mixture of chlorimuronethyl and metsulfuron methyl) as postemergence over preemergence application of pendimethalin in direct-seeded rice provided effective control of annual grasses, broadleaf weeds, and annual sedges (Table 6).

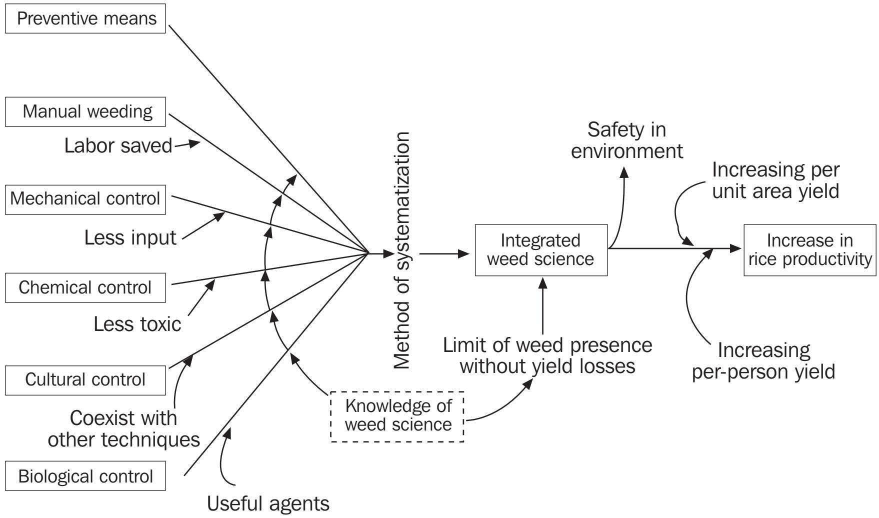

Fig. 8. A conceptual model of integrated weed control.

Table 6. Effect of herbicide combinations on weeds and yield of dry-seeded irrigated rice.

Treatment	Dose (g a.i. ha^{-1})	Weed density (no. m^{-2}) at 60 DAS			Grain yield (kg ha^{-1})
		Echinochloa spp.	*Caesulia axillaris*	Annual sedges	
Pendimethalin	1,000	1.4	108.0	181.4	3,639
Pendimethalin followed by 2,4-D	1,000 followed by 500	0.0	0.0	0.0	5,914
Pendimethalin followed by Almix	1,000 followed by 4	4.0	0.0	0.0	6,063
Weedy	–	94.5	2.7	170.7	1,011
Weed-free	–	–	–	–	6,319
LSD (P = 0.05)	–	–	–		511

Tank-mixed applications of anilofos and pendimethalin have been tried to reduce the pendimethalin dose as it is much costlier than anilofos (Table 7). Pendimethalin at half the recommended dose in combination with anilofos at 400 g ha^{-1} yielded on a par with the recommended dose of pendimethalin (1.0 kg ha^{-1}).

Conclusions

Direct seeding of rice is an economical alternative to transplanting rice. Weeds are the major constraint to the successful cultivation of direct-seeded rice since the emergence and growth of weeds

Table 7. Efficacy of tank-mix application of pendimethalin and anilofos on *Echinochloa* spp. and grain yield of dry direct-seeded irrigated rice.

Treatment	Dose (g a.i. ha^{-1})	*Echinochloa* spp. (no. m^{-2} at 60 DAS)	Grain yield (kg ha^{-1})
Pendimethalin	1,000	3.4	5,525
Anilofos	400	43.3	2,333
Anilofos	600	21.7	3,458
Pendimethalin + anilofos	1,000 + 400	0.0	5,479
Pendimethalin + anilofos	500 + 400	14.7	5,279
Pendimethalin + anilofos	500 + 600	1.2	5,369
Weedy	–	103.3	1,333
Weed-free	–	–	6,028
LSD (P = 0.05)		–	497

start simultaneously with those of rice. Therefore, appropriate and economical weed management technology is required to be developed for the sustainable cultivation of direct-seeded rice. The adoption of any one method of weed control, whether cultural, mechanical, or chemical, may not provide effective weed control in direct-seeded rice. Therefore, an integrated strategy of weed management is needed for the sustainable production of direct-seeded rice.

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Notes

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Studies on weed and water management in direct-seeded rice

S.V. Subbaiah

Experiments were conducted at the Directorate of Rice Research from 1997 to 2003 at different locations across the country. Results showed that butachlor + safener and pyrazosulfuron-ethyl and almix + surfactant were effective at most locations, followed by pretilachlor + safener. In general, butachlor + safener was effective against grassy weeds, whereas pretilachlor + safener exhibited efficacy against both grasses and sedges. Pyrazosulfuron-ethyl tested at low dosages was effective against sedges and broadleaf weeds, and to some extent against grassy weeds, whereas almix + surfactant was effective mainly against broadleaf weeds. Experiments indicated that there is scope to reduce the number of puddlings in rice if effective weed control is practiced with RoundUp CT application before puddling, followed by butachlor application 6–8 days after sowing/planting under two puddlings in all three methods (broadcasting in puddled soil, drum seeding, and transplanting) of crop establishment. It is also possible to reduce the water requirement in row seeding vis-à-vis broadcasting and transplanting. Iron deficiency during the early growth period of direct-seeded rice will be severe because of poor water management. Soil application of iron (25–30 kg Fe ha^{-1}) is less effective, especially on calcareous soils. Foliar application ($FeSO_4$) is most economical. Non-neutralized solution of 2–3% of $FeSO_4$ proved more effective if sprayed 2–3 times at 7–10-day intervals.

It is a fact that direct-seeded rice is more prone to severe weed competition than transplanted rice. Direct dry seeding encourages more weed growth than direct wet seeding, which is sown after puddling and leveling the land. Weed problems are in general less in transplanted or direct-seeded rice grown on puddled soil. Hence, appropriate weed strategies are to be formulated taking into consideration stand establishment practices, which also depend on water management practices. Mostly, dry seeding is confined to rainfed upland areas and wet seeding to irrigated lowland and upland areas. Rainfed upland rice is grown on an area of 6.1 million ha in India, covering Assam, Bihar, Jharkhand, Orissa, Chhattisgarh, Madhya Pradesh, eastern Uttar Pradesh, and West Bengal. Another 1 million ha is distributed in other states. This paper deals primarily with the wet seeding of rice in India.

Table 1. Treatment schedule for weed control trials conducted at various sites in India.

Treatment	Detail
T1	Anilofos at 0.3 kg a.i. ha^{-1}
T2	Butachlor at 1.0 kg a.i. ha^{-1}
T3	Clomozone at 0.2 kg a.i. ha^{-1}
T4	Clomozone at 0.4 kg a.i. ha^{-1}
T5	SIL.994 (butachlor + safener) at 1.0 kg a.i. ha^{-1}
T6	SIL.994 (butachlor + safener) at 1.5 kg a.i. ha^{-1}
T7	Sofit (pretilachlor + safener) at 1.0 kg a.i. ha^{-1}
T8	Sofit (pretilachlor + safener) at 1.5 kg a.i. ha^{-1}
T9	Rogue (butachlor + 2,4-DEE) at 1.0 kg a.i. ha^{-1}
T10	Rogue (butachlor + 2,4-DEE) at 1.5 kg a.i. ha^{-1}
T11	Anilofos 0.3 kg ha^{-1} + trichlopyr 0.3 kg ha^{-1}
T12	Anilofos 0.3 kg ha^{-1} + trichlopyr 0.5 kg ha^{-1}
T13	Hand weeding twice at 25 and 50 DAS
T14	Weedy check

Weed flora and herbicide selection

Crop establishment and weed control techniques are critical in rice farming, especially in direct-seeded rice. It is not uncommon to observe wet-seeded rice fields smothered by weeds, mainly grasses and broadleaf weeds (Moody 1992). In transplanted rice, young seedlings establish early and compete well with emerging weeds; standing water also suppresses weeds. However, weed competition is more severe in wet-seeded rice as weed seeds germinate simultaneously with the rice seeds. The phenotypic appearance of grassy weeds, especially *Echinochloa colona* and *E. crus-galli,* closely resembles that of rice seedlings and it is difficult to differentiate such weeds and remove them in the early stages. Manual weeding has become difficult because of labor scarcity and increased cost. Application of preemergence herbicide is an effective method for controlling weeds in the early stages. Studies on bioefficiency, toxicity, and residual effects as well as economic efficiency are limited in direct-seeded rice. Hence, weed control and herbicide studies on direct seeding were undertaken at the Directorate of Rice Research (DRR) during 1999 and the results are summarized as follows.

Weed flora consisted of grasses, sedges, and broadleaf weeds. Among the grasses, *E. crus-galli* was predominant, followed by *Cyperus difformis* in sedges and *Ammannia baccifera*, *Eclipta prostrata*, and *Sphenoclea zeylanica* in broadleaf weeds right from the initial stages in direct-seeded rice. The order of weed dominance was 58% broadleaf weeds, 20% sedges, and 17% grasses at the DRR farm, which varies with location.

Reduction in grain yield because of *E. crus-galli* was 47% and 53% for infestation up to 60 and 75 days after sowing (DAS), respectively. It was observed that rice–*E. crus-galli* competition up to 30–45 DAS can be tolerated in wet-seeded rice invertisols (deep black soils) of Hyderabad. Out of seven herbicides tested for preemergence application (Table 1), butachlor + safener at a lower dose of 1 kg a.i. ha^{-1} gave grain yields equivalent to those of two hand weedings (Table 2), and recorded higher gross and net returns of US$746 and $517 ha^{-1}, respectively, with a higher benefit-cost ratio (3.26), followed by butachlor + 2,4-D EE at 1.0 kg a.i. ha^{-1} (Table 3) (Ramamurthy 1999).

Table 2. Effect of weed control on grain yield of wet-seeded rice and germination of succeeding crop after rice at the DRR farm, Hyderabad, India, 1998 and 1999.

Treatment	Grain yield (t ha^{-1})			Germination %				Mean	
	1998-99 (winter)	1999 (rainy season)	Mean	1998-99		1999		Black gram	Sunflower
				Black gram	Sunflower	Black gram	Sunflower		
T1	4.4	4.1	4.2	82	50	62	48	72	49
T2	4.9	4.2	4.5	85	61	70	49	78	55
T3	5.3	3.9	4.6	60	35	51	45	56	40
T4	4.0	4.3	4.1	34	18	50	37	42	28
T5	6.4	4.8	5.6	87	52	75	65	81	59
T6	6.1	4.3	5.2	76	45	90	60	83	53
T7	5.1	4.1	4.6	65	29	66	42	66	36
T8	5.0	4.0	4.5	54	21	60	32	57	27
T9	5.4	4.4	4.9	51	14	60	35	56	25
T10	4.0	4.0	4.0	38	8	58	35	48	22
T11	4.6	4.2	4.4	44	16	66	40	55	28
T12	4.4	4.2	4.3	40	11	50	48	45	30
T13	6.2	4.7	5.5	91	78	81	90	86	84
T14	2.1	3.2	2.6	84	67	90	85	87	76
LSD (0.05)	0.2	0.4	–	na[a]	na	na	na	–	–

[a]na = not analyzed.

Table 3. Economics of different weed control treatments.[a]

Treatment	Total cost of cultivation (Rs. ha^{-1})	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	Benefit-cost ratio
T1	8,970	20,442	11,472	2.28
T2	9,170	22,430	13,260	2.45
T3	9,010	24,452	15,442	2.71
T4	9,170	18,344	9,174	2.00
T5	9,170	29,852	20,682	3.26
T6	9,330	27,774	18,444	2.98
T7	9,570	23,610	13,590	2.47
T8	9,930	23,330	13,400	2.35
T9	9,300	25,124	15,824	2.70
T10	9,525	18,582	9,057	1.96
T11	9,150	21,446	12,296	2.34
T12	9,180	20,372	11,192	2.22
T13	11,800	28,792	16,992	2.44
T14	8,850	9,952	1,102	1.12

[a]Cost of labor (men) = Rs. 140 d^{-1}, cost of labor (women) = Rs. 130 d^{-1}, cost of grain kg^{-1} = Rs. 4, cost of straw t^{-1} = Rs. 500, US$1 = Rs. 40.

Weed indices

Several weed indices were worked out using the formula of Misra and Misra (1997):

1. Weed persistence index (WPI)

$$\text{WPI} = \frac{\text{Dry weight of weeds in treated plot}}{\text{Dry weight of weeds in control plot}} \times \frac{\text{Weed density in control plot}}{\text{Weed density in treated plot}}$$

2. Crop resistance index (CRI)

$$\text{CRI} = \frac{\text{Dry matter production (DMP) by crop in the treated plot}}{\text{DMP by crop in the control plot}} \times \frac{\text{DMP of weeds in control plot}}{\text{DMP of weeds in treated plot}}$$

3. Weed management index (WMI)

$$\text{WMI} = \frac{\text{Percent yield over control}}{\text{Percent control of weeds}}$$

4. Agronomic management index (AMI)

$$\text{AMI} = \frac{\text{Percent yield – percent control of weeds}}{\text{Percent control of weeds}}$$

5. Integrated weed management index (IWMI)

$$\text{IWMI} = \frac{\text{WMI + AMI}}{2}$$

Higher CRI, WMI, AMI, and IWMI values were obtained with low WPI under butachlor + safener and hand weeding twice treatments (Table 4). The unweeded check recorded a higher WMI and lower CRI, AMI, and IWMI values compared with other weed control treatments. Regression analysis (Ramamurthy 1999) showed that every kg increase in weed dry matter resulted in a decrease of nearly 3.4 kg of rice grain yield (Table 5).

Herbicide residue

To apply feasible, economically viable, and eco-friendly technology for increased food production, it is important to be careful in applying chemicals. Residue analysis indicated that clomozone at 0.4 kg a.i. ha^{-1} is highly toxic to rice plants and the detectable residue level in the rice grain was nearly 3 ppm, which could be highly toxic to humans and animals (Table 6). Rice grain had a residue of 1 ppm clomozone at 0.20 kg a.i. ha^{-1}; however, that might not be much toxic to plants and animals. In postharvest soil samples, the residue of the same herbicide at both doses was found to be far below the maximum permissible limit of 1 ppm. Also, it was observed that the germination of succeeding blackgram seed in a butachlor + safener–treated plot was comparable with that of nonherbicide plots. However, sunflower germination was poor in all herbicide-applied plots, and more severe at higher doses (Table 2). This indicates that sunflower should not be grown as a succeeding crop within 10 days after the rice harvest if herbicides were applied.

Table 4. Effect of weed control on various agronomic indices in rice 75 days after sowing.[a]

Treatment	WPI	CRI	WMI	AMI	IWMI
T1	0.72	7.09	1.71	0.71	1.21
T2	0.88	6.12	1.99	0.99	1.49
T3	0.43	18.97	1.92	0.92	1.42
T4	0.64	10.91	1.05	0.06	0.56
T5	0.66	28.10	2.40	1.40	1.90
T6	0.86	21.70	2.16	1.16	1.66
T7	0.80	11.01	2.10	1.11	1.60
T8	0.82	10.71	1.85	0.86	1.36
T9	0.98	8.39	2.09	1.09	1.59
T10	1.00	6.41	1.16	0.17	0.67
T11	0.59	10.24	1.73	0.74	1.24
T12	0.70	7.86	1.58	0.58	1.08
T13	0.68	22.57	2.45	1.45	1.95
T14	1.00	1.00	0.00	0.00	0.00

[a]WPI = weed persistence index, CRI = crop resistance index, WMI = weed management index, AMI = agronomic management index, IWMI = integrated weed management index.

Table 5. Correlation and regression equation as influenced by weed control treatments (y = a + bx).

Y	X	Regression equation	r^2
Grain yield (kg ha^{-1})	Weed DMP[a] (kg ha^{-1})	Y = 5,743.30 – 3.37x	0.599
Grain yield (kg ha^{-1})	Crop DMP (kg ha^{-1})	Y = 1,322.27 + 0.98x	0.797
Grain yield (kg ha^{-1})	Leaf area index	Y = 2,806.45 + 1904.48x	0.795
Grain yield (kg ha^{-1})	Panicles m^{-2}	Y = 2,085.99 + 18.31x	0.771
Grain yield (kg ha^{-1})	Filled grains $panicle^{-1}$	Y = 162.33 + 34.71x	0.824

[a]DMP = dry matter production.

Herbicides for effective control of weeds in direct-seeded rice

Preemergence application of anilofos + trichlopyr at 300 g ha^{-1} each recorded higher grain yield of wet-seeded rice, closely followed by anilofos + trichlopyr at 300 g and 200 g ha^{-1} treatment, respectively (Table 7). This was mainly because of more production of panicles owing to better weed control efficiency. Anilofos + trichloyr at 300 + 400 g ha^{-1} and cyhalofop-butyl at 80 g ha^{-1} were found effective in controlling major and total weeds, dry matter production, and, hence, grain yield.

Crop establishment method vs. weed control practices

Proper stand establishment technique is one of the most effective cultural methods for weed control. To ensure this, farmers use a very high seed rate. There are several ways to control weeds culturally, such as seed rate, line sowing, spacing, intercropping, and hoeing, which form an essential part of integrated weed management practices.

Table 6. Herbicide residues in postharvest soil, rice grain, and straw.

Treatment	Dose (kg a.i. ha^{-1})	Residue (ppm)		
		Soil	Grain	Straw
Butachlor	1.00	0.002	0.0002	0.0004
Butachlor + safener	1.50	0.004	0.0006	0.0007
Anilofos	0.30	0.004	0.0005	0.0006
Pretilachlor + safener	1.50	0.005	0.007	0.0008
Clomozone	0.20	0.030	1.080	1.520
Clomozone	0.40	0.090	3.030	3.920

Table 7. Effect of weed control treatments on weeds and rice.

Treatments	Weed		Rice	
	Population (no. m^{-2})	Dry wt. (g m^{-2})	No. of panicles m^{-2}	Grain yield (kg ha^{-1})
Cyhalofop-butyl at 60 g ha^{-1}	19.08 (365)	165	109	3,460
Cyhalofop-butyl at 70 g ha^{-1}	19.43 (378)	169	116	3,520
Cyhalofop-butyl at 80 g ha^{-1}	17.76 (316)	154	122	3,890
Trichlopyr at 500 g ha^{-1}	16.12 (260)	134	119	3,490
Anilofos + trichlopyr at 300 + 200 g ha^{-1}	15.88 (253)	126	149	4,850
Anilofos + trichlopyr at 300 + 300 g ha^{-1}	15.28 (235)	105	152	4,910
Anilofos + trichlopyr at 300 + 400 g ha^{-1}	14.54 (211)	100	150	4,720
Weedy check	24.23 (588)	277	71	1,480
Two hand weedings at 20 and 40 days after sowing	20.88 (438)	168	107	2,950
LSD (P = 0.05)	1.84	63	23	690

The data on weed management revealed that, among different methods of crop establishment, transplanting seedlings at 20 cm × 10 cm and row seeding at 20-cm spacing were on a par and recorded significantly higher yields than other treatments during both the rainy and winter seasons of 1995-96 (Table 8). The broadcasting method recorded significantly lower yields than other sowing treatments because of difficulty in controlling weeds. For weed control practices, weed-free situations recorded significantly higher yield, followed by herbicide application, that is, pretilachlor + safener. The unweeded check produced the lowest yield. Hand weeding twice recorded significantly higher yield than the unweeded check but lower yield than the herbicide treatment and weed-free situation.

The economics of the combinations of crop establishment and weed control methods appears in Table 9. The total cost of cultivation was the highest (Rs. 5,519 ha^{-1}) for transplanting and lowest (Rs. 3,356 ha^{-1}) for broadcasting. Gross returns and net returns for direct seeding and transplanting were similar. The benefit-cost (BC) ratio was the highest (4.98) for row seeding by a drum seeder of rice with 20-cm spacing plus herbicide (pretilachlor + safener at 0.6 kg ha^{-1}) as preemergence spray at 3 days after sowing. This was on a par with transplanting plus the weed-free situation in terms of yield and BC ratio (Table 9).

Table 8. Grain yields under different crop establishment and weed control methods in wet-seeded rice at the DRR farm, Hyderabad, 1995-96.

Treatments	Grain yield (t ha^{-1})	
Planting treatments	1995 kharif	1995-96 rabi
M1 (20-cm line spacing by DRR row weeder)	4.92	5.96
M2 (15-cm line spacing by DRR row seeder)	4.61	5.69
M3 (transplanting, 20 × 10 cm)	4.88	5.99
M4 (broadcasting)	3.08	5.30
CD (0.05)	0.19	0.16
Weed control practices		
S1 (pretilachlor + safener)	5.96	4.61
S2 (hand weeding twice)	5.76	4.66
S3 (weed-free situation)	6.16	4.87
S4 (weedy check)	5.07	3.57
LSD (0.05)	0.10	0.11

Table 9. Economics of row seeding and weed control treatments (Rs. ha^{-1}) over two seasons of 1995-96.

Treatment		Cost of cultivation (Rs. ha^{-1})	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	BC ratio
M1	S1	3,388	16,860	13,472	4.98
	S2	3,568	15,889	12,321	4.45
	S3	4,503	19,498	14,995	4.33
	S4	3,028	12,203	9,175	4.03
M2	S1	3,652	15,660	12,208	4.56
	S2	3,635	15,684	11,865	4.26
	S3	4,566	19,086	14,520	4.18
	S4	3,092	12,275	9,183	3.97
M3	S1	6,785	16,604	11,819	3.47
	S2	4,965	16,740	11,775	3.37
	S3	5,900	19,464	13,564	3.30
	S4	4,425	12,645	8,220	2.86
M4	S1	3,070	9,732	6,662	3.17
	S2	3,250	9,739	6,689	3.00
	S3	4,185	11,895	7,710	2.86
	S4	2,920	8,048	5,128	2.75

Source: DRR (1995, 1996).

Effect of weed densities on grain yield under direct-seeded rice in puddled conditions

Eleven weed control treatments were tested in direct-seeded rice under puddled conditions (T1 = *Echinochloa*, 2 plants m^{-2}; T2 = *Echinochloa*, 3 plants m^{-2}; T3 = *Echinochloa*, 4 plants m^{-2}; T4 = *Echinochloa*, 5 plants m^{-2}; T5 = *Echinochloa*, 6 plants m^{-2}; T6 = only grassy weeds; T7 = only sedges; T8 = only broadleaf weeds; T9 = hand weeding twice; T10 = butachlor at 1.5 kg a.i. ha^{-1}; and T11 = weedy check).

Table 10. Effect of weed densities on grain yield (t ha^{-1}) under direct-seeded rice in puddled conditions in 2003.

Treatment	Grain yield (t ha^{-1})
T1 *Echinochloa,* 2 plants m^{-2}	3.88
T2 *Echinochloa,* 3 plants m^{-2}	3.12
T3 *Echinochloa,* 4 plants m^{-2}	2.66
T4 *Echinochloa,* 5 plants m^{-2}	1.85
T5 *Echinochloa,* 6 plants m^{-2}	1.74
T6 Grassy weeds only	1.74
T7 Sedges only	3.24
T8 Broadleaf weeds only	3.12
T9 Hand-weed twice	4.63
T10 Butachlor (1.5 kg a.i. ha^{-1})	4.40
T11 Weedy	1.62
LSD (0.05)	0.50

Source: DRR (2003).

The mean maximum grain yield (4.63 t ha^{-1}) was recorded under two hand weedings, followed by butachlor (4.40 t ha^{-1}) (Table 10). Grain yield was influenced by the density of *Echinochloa*. The mean maximum grain yield (3.88 t ha^{-1}) was recorded when only 2 plants of *Echinochloa* were present and the yield decreased with increases in the density. Among grassy weeds, sedges, and broadleaf weed populations, the significantly lowest grain yield (1.74 t ha^{-1}) was recorded under grassy weeds only.

Techniques for growing direct-seeded rice under puddled conditions

Based on the results of coordinated trials during 2001 (out of 11 locations), inferences can be drawn that irrespective of the soil type, the direct seeding of sprouted seed with an 8-row drum seeder, 6 hours after puddling, using herbicide at 4–6 DAS followed by the application of recommended fertilizer is a suitable management practice and is better than broadcasting of sprouted seed and also the farmers' method of transplanting and application of the recommended fertilizer dose as basal. The delay in sowing with a drum seeder (24 h after final puddling) was found promising only at Pusa and Patna in silty loam and clay loam soils, respectively. Increased grain yield with the drum seeder practice over the broadcast method was 15% when averaged over 10 locations (Table 11). The average yield over 10 different locations and varieties revealed that transplanting in lines recorded a marginal mean grain yield increase to 4.88 t ha^{-1} vis-à-vis seeding of sprouted seed with an 8-row drum seeder (4.51 t ha^{-1}).

Conclusions on weed management trials

Weed management experiments conducted at the DRR farm, Hyderabad, India, showed that only a few herbicides such as butachlor + safener and butachlor +2,4-DEE at 1.0 kg a.i. ha^{-1}, pretilachlor + safener at 0.4 kg a.i. ha^{-1}, and anilofos + trichlopyr at 300 g a.i. ha^{-1} were effective as preemergence herbicides in wet-seeded rice because of their control of a wide spectrum of weed flora and increasing rice yields equivalent to grain yield obtained in hand weeding twice. However, inconsistent results obtained from the coordinated weed control trials conducted in many locations clearly illustrate that an integrated weed management practice con-

Table 11. Techniques for growing direct-seeded rice under puddled conditions during kharif 2001.

Treatment	Ragolu	Mandya	Siriguppa	Aduthurai	Varnasi	Faizabad	Jagadalpur	Karjat	Pusa	Patna	Titabar	Mean
T1	7.30	5.74	6.72	4.49	3.29	4.56	3.02	3.31	3.80	3.55	3.23	4.17
T2	6.13	6.68	5.47	5.50	5.05	4.98	4.63	3.78	4.51	4.41	3.71	4.87
T3	8.40	6.76	5.91	4.10	3.21	4.33	2.85	2.90	3.57	2.98	2.54	3.92
T4	7.75	7.42	6.25	4.46	4.52	4.83	4.28	3.64	3.59	3.42	2.40	4.48
T5	7.23	7.05	6.19	4.64	4.36	4.68	3.92	3.27	4.25	3.89	2.81	4.51
T6	5.78	6.97	6.07	4.71	3.97	4.27	3.87	2.97	4.00	2.89	2.66	4.24
T7	6.15	7.45	5.73	4.42	4.63	4.33	3.48	3.41	3.78	3.73	3.00	4.40
T8	–	7.58	–	4.13	–	–	–	–	4.67	3.26	–	–
LSD (0.05)	ns	0.86	0.56	0.36	0.43	0.22	0.53	0.34	0.24	0.77	0.75	
Variety	RGL-2332	BR-2655	IET-14238	ADT-43	Narendra-118	Sarjoo-52	Mahamaya	Karjat-3	Sujata	Sita	Luit	
Soil type	Red loam	Red sandy loam	Clay	Clay	Sandy loam	Sandy loam	Clay loam	Clay loam	Silty clay	Clay	Clay loam	
pH	7	7.1	7.7	7.1	7.2	7.4	7.1	7.1	8.4	7.2	4.9	
Rec. NPK + Zn (kg ha^{-1})	80-50-50-50	100-50-50-20	150-60-60	125-50-50-25	90-40-40	120-60-60-25	80-50-30-25	100-50-50	80-40-20-25	80-40-20-25	40-20-20	

Treatment details

T1 Farmers' practice of TP + recommended fertilize dose (125:50:50 kg NPK ha^{-1}) + manual weeding.

T2 Transplanting in lines + herbicide 4–6 DAT + recommended NPK (N in splits, 50% basal + 25% at tillering + 25% at PI, P and Zn basal, K 75% basal + 25% at PI).

T3 Broadcasting of sprouted seed + weed and fertilizer management as in T1.

T4 Seeding of sprouted seed through 8-row drum seeder on same day, herbicide and fertilizer application as in T2.

T5 Seeding as in T4 + herbicide application followed by spot weeding + recommended NPK (N in 3 splits, 1/3 N at 15–20 DAS, 1/3 N at 31–40 DAS, and 1/3 N at 48–56 DAS), P, Zn, and K as in T2.

T6 Seeding of sprouted seed through 8-row drum seeder 24 h after puddling + herbicide and fertilizer as in T5.

T7 Seeding as in T4 + herbicide as in T5, fertilizer as in T2.

T8 Seeding throwing method of planting + weed and fertilizer management as in T2.

sisting of preemergence herbicide application at 3–7 DAS + interrow cultivation with a cono/rotary weeder at 25 days after seeding + one hand weeding at 45 DAS could be recommended for direct-seeded rice.

Water management in wet-seeded rice

Fresh water is vital for human life. The per capita availability of fresh water is decreasing in most parts of the world because of population growth and industrialization. In general, when available fresh water falls below 1,000 m^3 per capita per year, countries experience chronic water scarcity that will affect economic development and human health and well-being. The annual per capita availability of fresh water in India is 2,464 m^3 compared with 19,428 m^3 for the former Soviet Union. The annual per capita water availability in India may go down from 2,464 m^3 in 1990 to an estimated 1,496 m^3 in 2025, when the population is likely to be around 1.4 billion. Compare this situation with a country such as Israel that is currently surviving on much less (401 m^3) fresh water per person per annum. Therefore, it is vital to develop new methods and technologies to conserve water in all sectors, including agriculture.

Irrigated agriculture, especially flooded rice, consumes a large share of the available water in India. The actual water requirement of rice crops depends on soil type, season, varietal duration, and temperature, as well as cultural practices, including crop establishment. Transplanting of rice has been the widely adopted crop establishment practice in the irrigated ecology. Field experiments and farmer surveys in the Upper Pampanga River Integrated Irrigation Systems (UPRIIS) in the Philippines show that wet-seeded rice is becoming increasingly popular because of savings in water and other advantages (Bhuiyan et al 1994).

In clay soils (Vertisol) around Hyderabad, water management in the beginning is critical for wet direct-seeded rice in puddled soil, that is, up to 10 DAS in the monsoon (*kharif*) season and up to 15 DAS in the winter/dry (*rabi*) season. Proper land preparation and leveling will ensure uniform spread of water during irrigation and facilitate drainage when required. The soil must be allowed to settle for a day before drum seeding to facilitate movement of the seeder. Maintenance of the soil under saturation or with a thin film of water is necessary to have uniform germination and optimum plant stand. Any drought with cracking of soil soon after seeding leads to iron deficiency, particularly during the winter season, and the low temperatures further reduce the plant stand. A thin layer (1–2-cm depth) of standing water is essential at the time of herbicide (soil-applied) application for the uniform spread of the chemical and effective weed control. Draining of water from the fields in the morning and reapplying water late in the evening hours is necessary to maintain adequate soil temperature for good germination and early growth during the winter months of December and January.

Once the plant stand is established, there is no difference in water management practices between transplanted and direct-seeded rice. Depending on the evapo-transpiration rates (3.0 to 9.0 mm d^{-1} in the monsoon/kharif and 3.5 to 11.0 mm d^{-1} in the rabi season in the Hyderabad area), the irrigation water demand for rice varies with different water management practices. Rice variety Rasi (nonlodging type, duration 120 d) used 117 cm of irrigation water under continuous shallow submergence and 72 cm under cyclic submergence or intermittent irrigation (Table 12). The corresponding water-use productivity (WUP) for the two systems was 41 and 64 kg grain per ha-cm of water used (Subbaiah and Pillai 1995). This is substantially higher than the national average value for WUP in India, where water-use efficiency is lower than in other countries in the world (Table 13).

Table 12. Irrigation water requirement, water-use efficiency, and productivity of rice during the 1995 rabi season, DRR, Hyderabad, India.

Variety	Treatment	Grain yield (t ha^{-1})	Average water required (cm)	Average water used (cm)	WUE (%)	WUP (kg grain ha-cm^{-1})
IET 1444	Continuous submergence	4.74	63.6	117.0	54.3	40.8
	Cyclic submergence	4.62	63.6	72.0	88.2	64.2
	Continuous submergence with mid-season drainage	4.75	63.6	115.5	55.0	41.1
RP 4-14	Continuous submergence	5.63	81.5	120.0	67.0	46.9
RP 79-2	Continuous submergence	5.90	85.1	120.0	70.9	49.2

[a]WUE = water-use efficiency = water required divided by water used, WUP = water-use productivity = kg grain per ha-cm of water used.

Table 13. Grain yield and water-use productivity (WUP) of rice in different countries.

Country	Grain yield (t ha^{-1})[a]	WUP[b] (kg grain ha-cm^{-1})	WUP[c] (kg grain ha-cm^{-1})
Japan	6.01	40.1	50.1
China	6.01	40.1	50.1
India	2.77	18.5	23.1
United States	6.27	41.8	52.3
Egypt	8.17	54.5	68.1
Vietnam	3.63	24.2	30.3
Indonesia	4.34	29.0	36.2
World	3.69	24.6	30.7

[a]FAO Production yearbook 1995. [b]Values worked out assuming 1,500 mm ha^{-1} of water requirement. [c]Values worked out assuming 1,200 mm ha^{-1} of water requirement.

Water-use productivity in crops, especially in rice, also depends on land preparation, stand establishment technique or tillage system, weed and fertilizer management practices, and irrigation techniques.

The conservation tillage experiments conducted at the DRR farm during the 1998-99 winter (*rabi*) season indicate that the total quantity of water required was 94.7 cm ha^{-1} for broadcast-sown rice, 59.2 cm ha^{-1} for drum-seeded rice, and 86.5 cm ha^{-1} for transplanted rice (cv. Krishnahamsa). These values do not include the water used for land preparation. A net savings in water of 31% is possible when drum seeding is adopted on puddled soil (Table 14). There is also scope for reducing the number of puddlings for rice if effective weed control is practiced. Herbicides such as Round-up are used for conservation tillage, which requires only two puddlings. A follow-up application of butachlor at 6–8 days after sowing/planting is needed to control weeds under all three crop establishment methods (DRR 1998, 1999).

In irrigated farming, the daily consumptive use of water for rice varies from 6 to 10 mm. Of the total water requirement of about 1,240 mm, evaporation accounts for

Table 14. Influence of seeding method on grain yield, weed dry matter (WDM), and irrigation water use at the DRR farm, Hyderabad, India, 1998-99.

Method of seeding	Grain yield ($t\ ha^{-1}$)	WDM ($kg\ ha^{-1}$)	Irrigation water ($cm\ ha^{-1}$)
Row seeding	3.43	76.2	59.2
Broadcasting	3.30	92.2	94.7
Transplanting	4.30	68.4	86.5

180–380 mm, transpiration 200–500 mm, and percolation 200–700 mm. The rice nursery requires about 40 mm (3%), land preparation about 200 mm (16%), and crop consumption in the main field about 1,000 mm (81%). The water requirement of rice varies with growth stage. The depth of water to be maintained should therefore be adjusted to suit the actual requirement at different growth stages. Based on the results of several field experiments, the following water management practices are suggested that could save as much as 30% in water requirement:

- The field must be flooded before puddling. Thorough puddling (lengthwise and crosswise) will create an impermeable layer (at 12–15-cm depth) that will reduce percolation losses and minimize weed infestation. After puddling, perfect leveling is necessary for efficient water management.
- If organic manure (paddy straw compost or cattle manure) is applied, water has to be drained for a few days to hasten the decomposition of the organic manure. This must be done well in advance (at least 3 wk ahead) of the time of basal application of fertilizer.
- After basal application and incorporation of fertilizer into the soil, a 2-cm layer of water should be maintained to reduce nitrogen losses and weed growth.
- Saturated soil or soil with a film (2-mm depth) of water is ideal for wet seeding and it will facilitate the germination and establishment of an optimum number of seedlings per unit area (50–75 m^{-2}).
- Soon after seeding, flush irrigation can be given to maintain saturated soil conditions for the first 10 to 15 DAS. Thereafter, continuous shallow submergence (2–3-cm depth) or cyclic submergence with intermittent irrigation can be practiced up to panicle initiation.
- During tillering, a 2-cm depth of water is sufficient. If the water depth is more or less than 2 cm, it reduces tillering.
- Draining the field for 3 d at about 30 DAS (midseason drainage) will help to promote root growth and reduce the development of nonproductive tillers.
- Application of urea on standing water results in high losses and lower availability of N. The field has to be drained to a very thin level of water 1 d before N topdressing. Farmers can re-flood the field 24 h after N application. Delay of more than 24 h in flooding the field after N fertilizer application results in higher N losses through nitrification-denitrification and leaching.
- If herbicide is to be applied, flooding to optimum water depth may be done before application.
- The field has to be drained gradually from 21 d after full flowering for proper harvest.

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Sedges in rice culture and their management

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Direct seeding of rice has been receiving increased attention recently in view of increased labor costs, scarcity of water, and increasing availability of chemicals for weed management. Research has so far demonstrated that the productivity of direct-seeded rice is comparable with that of transplanted rice if weeds are controlled. Although the availability of effective herbicides is expected to play an important role in the management of diverse weed problems, there are indications that problems of wild rice and sedges are likely to increase, particularly in direct-seeded rice. Sedges such as *Cyperus iria* and *C. difformis* are the major problems in both wet- and dry-seeding conditions, whereas *C. rotundus* and *Fimbristylis dichotoma* are dominant in rainfed uplands. *Scirpus maritimus* is a major problem in lowland rice. Different cultural practices such as summer tillage, crop rotation, intercropping, weed-competitive and allelopathic varieties, higher seed rate, and closer row spacing have been found effective in the suppression of sedges. Although effective and cheap herbicides are available for the control of grasses and broadleaf weeds in varying rice cultures, the availability of chemicals for the management of various groups of sedges is limited. Considering the diversity of weed problems in different rice cultures, no single method of control, whether cultural, manual, mechanical, or chemical, would be sufficient to provide season-long weed control under all situations. An integrated weed management system as part of an integrated crop management system would be an effective, economical, and eco-friendly approach for the management of sedges in rice. A detailed study on the biology and ecology of sedges is needed in order to formulate successful weed control measures.

Rice, one of the world's major food crops, is grown in diverse agroecological situations. Under intensified rice-cropping systems of today's agriculture, weeds have become a major pest of rice and perhaps the major constraint to rice farming. Weed species that cause problems in rice vary with soil, temperature, latitude, altitude, rice culture, seeding method, fertility, and water management and weed management practices (Smith and Moody 1979). Weeds are usually more severe in upland and dry-seeded rainfed rice than in irrigated transplanted rice. Out of about 350 species reported as weeds of rice, species of Cyperaceae (with more than 50) are ranked second in abundance after Poaceae (Akobundu and Fagade 1978, Holm et al 1977). Sedges are the dominant weeds of rainfed rice. They are similar to grasses but have three ranked leaves. The stems are usually triangular and they don't possess nodes and internodes. Several species of sedges have modified rhizomes, which are used for food storage and propagation.

Occurrence

Sedges infest rice cultivation in all agroecological situations. Some sedges, *Scirpus grossus*, *Eleocharis dulcis*, *Phragmites karka*, and *Cyperus iria*, are adapted to pH 4 and below (Grabial et al 1986). The types of sedges found in different rice cultures are listed in Tables 1 and 2. The distribution of sedges in rice in India is given in Table 3.

Interference of sedges in rice

Weeds compete severely for nutrients and, depending on the intensity of weed growth, the depletion may be up to 86.5 kg N, 12.4 kg P, and 134.5 kg K ha^{-1}, and, in addition, 61, 15, 2,523, and 166 g ha^{-1} each of Zn, Cu, Fe, and Mn, respectively, in fields dominated by *C. rotundus* (Malik and Moorthy 1996). Earlier, Bhardwaj and Verma (1968) reported that *C. rotundus* removed about 95 kg N, 5 kg P, and 80 kg K ha^{-1} and that more than 50% of these nutrients were contained in the tubers. Okafor and De Datta (1974) reported that *C. rotundus* competes with dryland rice for both moisture and nitrogen. In Iran, 128 plants m^{-2} of *Echinochloa crus-galli*, *C. rotundus,* and *C. difformis* reduced grain yield of transplanted rice by 19% (Dastghieb and Beibi 1988) and 256 plants m^{-2} of *E. crus-galli*, *C. difformis,* and *S. maritimus* reduced rice yield by 30% (Mirkamali 1985). *C.*

Table 1. Sedges in different rice cultures.

Taxonomy	Type	Rice culture	Competitiveness
Cyperus difformis	Annual	Direct-seeded (dry- or wet-seeded, irrigated or rainfed)/transplanted	Moderate
C. esculentus	Perennial	Direct-seeded (dry- or wet-seeded, irrigated or rainfed)	Moderate
C. imbricatus	Perennial	Transplanted	Low to moderate
C. iria	Annual	Direct-seeded (dry- or wet-seeded, irrigated or rainfed), direct-seeded upland (rainfed), lowland/transplanted	Moderate to high
C. rotundus	Perennial	Direct-seeded upland (rainfed)	High (competitive early)
C. serotinus	Perennial	Transplanted	Moderate
Eleocharis acicularis	Perennial	Transplanted	Moderate
E. kuroguwai	Perennial	Transplanted	Moderate
E. obtusa	Annual	Direct-seeded (dry- or wet-seeded, irrigated or rainfed)	Moderate
Fimbristylis dichotoma	Perennial	Direct-seeded upland (rainfed), lowland	Moderate
F. miliacea	Perennial	Direct-seeded upland (rainfed), lowland/ transplanted	Moderate (strong root competition)
F. littoralis	Annual/ perennial	Direct-seeded (dry-or wet-seeded, irrigated or rainfed)	Moderate
Scirpus hotarui	Perennial	Transplanted	Moderate
S. juncoides	Annual	Lowland, transplanted	Low to moderate
S. maritimus	Perennial	Lowland, transplanted	High

Source: Smith (1983).

Table 2. Sedges in deepwater rice.

Weed species	Country	Time of infestation
Cyperus rotundus	India, Bangladesh, Thailand	Before flowering
C. iria	India, Bangladesh, Thailand	Before flowering
C. difformis	India, Bangladesh, Thailand	Before and after flowering
C. pulcherrimus	Thailand	Before flowering
Eleocharis dulcis	India, Bangladesh, Thailand	Before and after flowering
E. plantaginea	Malaysia	Before and after flowering
Scirpus praelongatus	Malaysia	Before and after flowering
Pycreus spp.	Malaysia	After flowering
Fimbristylis littoralis	Thailand	Before flowering
F. sracilenta	Thailand	Before flowering

Source: Vongsaroj (1996).

Table 3. District-wise distribution of sedges in rice in India.

Weed species	Level of infestation				
	Very low	Low	Moderate	High	Very high
Cyperus compressus	2	–	–	–	–
C. difformis	26	3	19	11	2
C. esculentus	2	2	2	3	–
C. flavidus	4	–	–	–	–
C. halpan	–	–	–	–	2
C. iria	15	22	35	52	24
C. kyllinga	–	–	1	–	–
C. luzula	–	–	1	–	–
C. rotundus	18	10	14	10	11
C. stoloniferus	–	8	–	1	–
Eleocharis pelustris	–	1	–	–	–
E. acutangula	14	–	2	4	–
E. afflata	–	–	1	–	–
E. capitata	–	1	–	–	–
Fimbristylis barbata	–	1	3	–	–
F. dichotoma	–	2	2	–	19
F. littoralis	2	–	–	–	2
F. miliacea	15	15	14	7	23
F. tenella	2	4	1	1	–
F. woodrowii	1	–	–	–	–

Source: Gogoi et al (2004).

Table 4. Rice yield loss from interference of sedges.

Group	Rice culture	Yield loss (%)	Reference
Cyperus iria	Direct-seeded (rainfed upland)	11–40	Moorthy and Das (1998)
C. difformis	Transplanted	49–90	Chang (1970)
C. difformis	Direct-seeded (dry- or wet-seeded, irrigated or rainfed)	33–44	Swain (1973)
C. rotundus	Direct-seeded upland (rainfed)	29–51	De Datta (1979)
Eleocharis kuroguwai and *C. serotinus*	Transplanted	59	De Datta (1977)
Scirpus maritimus	Transplanted	18–25	De Datta (1977)
S. maritimus	Transplanted	48	De Datta (1979)

difformis creates a more serious problem in direct-seeded rice than in transplanted rice because of the latter's growth advantage. It offers the greatest competition at pretillering and tillering. Swain et al (1975) recorded a linear relationship between rice yield and duration of *C. difformis* competition, with a yield reduction of 64 kg ha^{-1} for each day of competition up to tillering at high fertility, but only 28 kg ha^{-1} under low-fertility conditions (Table 4).

Critical period of competition

The critical period of crop-weed competition can be defined as "the shortest span of time in the ontogeny of crop growth when weeding will result in higher economic returns." This depends on the nature of the weed and crop, environmental conditions, and weed density. Grasses are usually the most dominant in competition during the early season, whereas sedges and broadleaf weeds dominate later in the season. Weed competition is more severe in dry-seeded upland situations than in puddle-seeded or transplanted rice culture. It has been estimated that the initial duration of 30–40 d of crop growth is critical in direct-seeded rice (Tewari and Singh 1991), whereas the removal of weeds as late as 70 d after transplanting increased paddy yield significantly (Singh et al 1991).

Weed shift

Continuous use of herbicides for the control of annual grasses shifted the dominant species from grasses to broadleaf weeds and sedges and from annuals to perennials. De Datta (1977) reported that continuous use of similar herbicides to control annual weeds in Korea has increased the problem of perennials, including *C. serotinus*, *S. polyrhiza*, *Eleocharis acicularis*, *E. kuroguwai,* and *S. hotarui*. In wetland rice fields of tropical Asia, the infestation of *S. maritimus* has increased. Continuous use of thiobencarb has led to a shift in population of *Eleocharis geniculata* and oxadiazon to *C. difformis* and *Scirpus juncoides* Roxb. (Hassan and Rao 1996). In India, continuous use of grass killers such as butachlor in rice has resulted in a shift of weed flora to sedges such as *C. iria*, *Scirpus* spp., and *Fimbristylis* spp. (AICRP-WC 2002-03).

Weed management methods

Cultural control

Most cultural practices can be regarded as a means of weed suppression and an increase in their efficiency would contribute to better weed control.

Tillage. Tillage is an important cultural practice to reduce the incidence of perennial weeds. In continuous rice where these weeds are the most invasive, autumn tillage as early as possible can physically cut the overwintering structures into small pieces and field drying will destroy them by desiccation. In the Philippines, tillage practices during the dry season decreased the prevalence of *C. rotundus* (Moody 1979). However, in the U.S., repeated tilling of the soil at 1–3-week intervals before dry-seeding rice did not control *Eleocharis* or *Cyperus* (Smith et al 1977). Land preparation during the dry season significantly reduced the number of *C. rotundus* plants (Moody 1980), but tillage close to the start of the rainy season increased it (Castin and Moody 1980). Depth of plowing also affects the population of sedges. In Japan, plowing to a depth of 15 cm in December resulted in better control of *Sagittaria pygmaea*, *C. monti,* and *Eleocharis kuroguwai* than rotary tillage to a depth of 10 cm or zero-tillage (Kusanagi 1977). Yingviwatanapong (1986) found that one plow with 3 discs at 3.0–12.5-cm depth reduced *E. dulcis* by 49%.

Water management. Water is the "best herbicide" to control weeds. Most weeds have an optimum soil moisture level below or above which growth is suppressed; hence, time, duration, and depth of flooding can be managed to suppress weed growth. Water depth can be used to control many weeds, but some species are relatively unaffected by water depth. Many sedges do not survive in upland conditions. *C. difformis* was reported to be dominant in submerged conditions (Nishida and Kasahara 1975). Keeping the field flooded after planting will kill some weeds and will slow the growth of others. In a pot-culture experiment, Mishra et al (2001) did not observe any weeds with flooding at 2.5–7.5-cm depth continuously after transplanting vis-à-vis saturated conditions where a maximum number of *C. iria* was noticed. In an earlier study, Mabbayad (1967) reported that sedges such as *F. miliacea* were predominant at zero water depth (soil saturation). Early flooding for the control of *E. crus-galli* increased problems of annual species of *Cyperus* and *Eleocharis* (Smith et al 1977). *C. difformis* and *Scirpus* spp. are obligate aquatic weeds. Neither can be controlled in water-seeded rice by regulating water depth. There is some evidence that *C. difformis* may be partially suppressed by 15–20 cm or deeper water but not *Scirpus* spp. These sedges will not establish under dry soil conditions. Thus, drill or dry seeding has been used to delay their emergence until the permanent flood, after the rice is well established and able to compete.

Fertilizer management. Fertilization affects weed growth in rice fields. Guh (1974) observed that sedges such as *Eleocharis kuroguwai* were dominant on low-fertility soils. The application of nitrogen without proper weed management tends to enhance the vigor and competitive ability of weeds. In Taiwan, for *C. difformis,* yield reductions were greater with high rates of nitrogen (78%) than with low nitrogen levels (53%) (Chang 1970). Okafor and De Datta (1976) reported that application of nitrogen benefited *C. rotundus* more than the upland rice. The weed's growth, development, and competitive ability increased with increased nitrogen, enabling it to compete more vigorously for moisture and further reduce light transmission to the crop. This indicated that weed control in upland rice is more important under high soil fertility conditions than under low soil fertility conditions. In a pot-culture study, Mishra et al (2001) obtained a lower population of *C. iria* at higher nitrogen (80–120 kg ha^{-1}) than at a lower amount (40 kg ha^{-1}) in transplanted rice. The time of nitrogen application also influences weed growth. With inadequate weed control, it is best not to apply N or to apply N at low amounts.

Crop rotation. Crop rotation can be used to minimize crop damage from weeds. Rotating crops having dissimilar life cycles or cultural conditions (so as to break the cycle of the weeds) is among the most effective of all weed control methods. Intensive cropping systems can increase the competitive ability of crops, thereby reducing weed pressure. Sedges, especially *C. rotundus* and *C. esculentus,* are sensitive to shading. A 30% shade reduced dry matter and tuber production by 32%, whereas 80% shade reduced dry matter and tuber production by 94% (Keeley and Thullen 1978). Growing competitive crops in rotation with cotton reduced the population of yellow nutsedge tubers by 97–99% within 3 years (Keeley and Thullen 1983). Earlier, Smith and Frans (1969) reported that growing rice in the United States for 10 years continuously increased the population of *C. iria* with time. In the Philippines, Jereza and De Datta (1977) observed constantly high levels of infestations of *S. maritimus* in transplanted rice grown continuously for 3 years. However, when upland crops were rotated with rice, *S. maritimus* infestations decreased, but *C. rotundus* infestations increased. *S. maritimus* reduced rice yields less in the rotated system than in continuous cropping.

Interrow cultivation. It may be profitable to harrow a wet-seeded crop when it is 3–4 wk old. This presses down both the rice and the weeds into the standing water in the field. After several days, the rice plants become erect while the weeds remain under the water and die. This technique is particularly effective in the suppression of *F. miliacea*. Farmers in Iloilo Province, Philippines, use a similar technique to control sedges such as *F. miliacea, C. difformis*, and *C. iria* (Moody 1990).

Rice cultivars. Short-stature, early-maturing, erect rice cultivars are less competitive with weeds than cultivars that are tall and have fast and vigorous early vegetative growth, a vigorous root system, high tillering, and drooping leaves. In Peru, rapid-growing cultivars during early growth stages were more competitive with *C. esculentus* (Kawano et al 1974).

Plant density and method of seeding. Weeds affect rice growth mostly at the seedling stage when plant density of rice is established. A good crop stand can minimize weed problems. Sowing of rice at increasing seed rates reduced the dry weight of *Scirpus dulcis* (Yingviwatanapong 1986). Nutsedge species lack a competitive edge with crops once the crops form a dense canopy. Both purple (*C. rotundus*) and yellow (*C. esculentus*) nutsedges were sensitive to shading (Keeley and Thullen 1978). A high sowing rate of 120 kg ha^{-1} is recommended to control broadleaf weeds and *C. difformis* (Hassan and Rao 1993). Singh (1997) indicated that bunching (seeding in clusters) and line seeding recorded lower infestation of *C. rotundus*, *C. difformis,* and *F. miliacea* in the rainfed medium-deep waterlogged rice ecosystem. A seed rate of 75–100 kg ha^{-1} significantly reduced the population and dry weight of *C. rotundus* and *C. iria* in rainfed upland rice (Moorthy 1997). Narrow row spacing in maize and soybean resulted in better control of *C. rotundus* and *C. esculentus* than wider row spacing (Chapel and Leasure 1980).

Seedling age. In transplanted rice, the use of tall, old seedlings raises the competitiveness of rice to weeds, thus minimizing *S. planiculmis* infestations (Zhang 1996).

Biological control

Mycoherbicides. The rust fungus *Puccinia canaliculata* (Schw.) Lagerh. has the potential to control yellow nutsedge (*C. esculentus*). Release of the pathogen early in the spring on the seedlings of yellow nutsedge reduced the plant population, tuber formation, and flowering (Phatak et al 1987). This mycoherbicide is being developed and commercialized in the United States for the control of yellow nutsedge (Phatak 1992). Research is needed to determine the potential of *P. canaliculata* as a mycoherbicide in rice. A valid approach would be to integrate *P. canaliculata* with registered chemical herbicides, such as bentazon and bensulfuron methyl.

Use of fish. The use of fish in rice-farming systems appears to be a sustainable approach for rice cropping and for weed control. In Indonesia, the combination of common carp and grass carp in the irrigated lowland rice–fish farming system provided good suppression of *F. miliacea*, *C. iria,* and *S. maritimus* (Pane and Fagi 1992).

Use of pigs. In certain parts of Tamil Nadu, where rice is grown traditionally, farmers are effectively managing the nutsedge (*C. rotundus*) problem by using pigs (Chinnamuthu 2004). Since the nutsedge tubers are succulent and sweet in taste, pigs are very fond of them. This is one of the best nutritious food materials for pigs. Pigs can easily remove the tubers even when the soil is hard.

If the soil is wet and plowed, it will be even easier for them to remove the tubers. Usually, the field is soaked with water and puddled well and the animals are allowed to feed on tubers. Each animal is able to eat 2 to 4 kg of tubers in one day. Some 62–75 animals per hectare can remove available tubers within a day.

Allelopathy. Rice plants produce natural chemicals that can suppress and kill weeds. They release toxic allelochemicals into the paddy, either as root exudates or from decaying plant materials. These allelochemicals have been known to control ducksalad and other aquatic weeds. Approximately 4% of the 10,000 rice accessions in the United States national small grains collection that have been tested exhibited some allelopathic activity (Dilday et al 1991).

In an experiment conducted in Arkansas, rice lines with high allelopathic activity, combined with straw of the same lines incorporated into the soil, controlled rice flatsedge (*C. iria*) almost as effectively as a tank mixture treatment of propanil and bentazon (Lin et al 1992). This research suggests that rice varieties that possess high allelopathic activity can control some problematic weeds, and may reduce the need for herbicides. Research is required to develop suitable cultivars with allelopathy, and to integrate biological control strategies with other pest management strategies.

Chemical control

Manual and mechanical methods used to control sedges in rice could not find much place among farmers because of the high labor cost, scarcity of labor during the critical period of weed competition, and unfavorable weather at weeding time. Under such situations, herbicides are becoming increasingly popular in major rice-growing areas as a viable alternative to hand weeding. Several herbicides (Table 5) have been used to control annual sedges in rice.

Application of thiobencarb + 2,4-D (3.0 + 1.0 kg ha^{-1}) at 25 days after sowing (DAS), thiobencarb + propanil (3.5 + 4.2 kg ha^{-1}) at 15 DAS, and monilate (3.5 kg ha^{-1}) at 10 DAS followed by 2,4-D at 25 DAS were found to be effective in controlling *C. difformis* and *C. longus* in direct-sown rice (Fatemi 1990). The combination of bentazon + 2,4-D (1.0 + 0.50 kg ha^{-1}) was more effective in controlling *S. maritimus* than applying bentazon alone at 2.0 kg ha^{-1} (Lubigan and Mercado 1977). Singh et al (2004) recorded the highest sedge control efficacy with almix + butachlor at 4 + 938 g ha^{-1} when applied at 3 days after transplanting (DAT). Similarly, a ready-mix formulation of anilofos + tryclopyr and anilofos + 2,4-D at 3–9 DAT more effectively controlled *C. iria* and *F. miliacea* than anilofos alone in transplanted rice (Singh et al 2003).

Integrated weed management

Weed-rice ecological relationships are never static. The continuous adoption of any particular rice production practice causes a shift in dominance and distribution of rice weeds. In the formation of weed management programs, the type of rice culture, cultivars grown, tillage, crop establishment methods, planting geometry, fertilizer application, and water management need to be systematically manipulated so as to create favorable conditions for crop growth, but unfavorable for weed survival. Manual and mechanical weeding in direct-seeded rice should be used only in conjunction with other cultural and chemical methods to minimize labor requirements where appropriate. The combination of tillage and chemical methods has been reported to be more effective in controlling *C. rotundus* than either tillage or chemical alone. Verhoeven and Cowdry (1961) observed a substantial reduction in tuber population of *C. rotundus* in the top 30 cm of soil when plowing to 25 cm deep was followed by disking and 2,4-D application at 4.4 kg ha^{-1}. Integration of pendimethalin (1.5 kg ha^{-1}) with *halode* (harrowing a wet-seeded crop into the standing water when it is 3–4 wk old) significantly decreased the dry matter of *Cyperus* spp. in direct-seeded upland rice (Angiras and Sharma 1998).

Table 5. Recommended herbicides for controlling sedges in different rice cultures.

Rice culture	Herbicide	Dose (g a.i. ha^{-1})	Time of application[a]	Sedges controlled	References
Transplanted	Acetachlor	100–330	3–8 DAT	*Scirpus juncoides*	Rajkhowa et al (2004)
Rice nursery	Pretilachlor plus safener	500	8 DAS	Sedges, grasses, and broadleafs	Balasubramanian et al (1997)
Transplanted/ direct-seeded	Pyrazosulfuron ethyl	20–25	Postemergence	*C. iria*	Chopra and Chopra (1993), Saha et al (2003), Maiti et al (2003)
Direct-seeded	Anilofos and dithiopyr	400	3–6 DAS	*C. iria, C. difformis, F. miliacea*	Malik et al (2002)
		180	3–6 DAS		
Direct-seeded puddled	2,4-DEE	1,000	20 DAS)	*C. iria* and *Scirpus* spp.	Angiras and Attri (2002
Puddled seeded	Butachlor	1,000	5–6 DAS	*C. difformis*	Moorthy and Saha (2002)
	Anilofos + ethoxysulfuron	250 + 10	10 DAS		
	Cinmethylin	50–75	7 DAS		
	Butachlor + safener	1,000	5–6 DAS	*F. miliacea*	
	Ethoxysulfuron	15	15–20 DAS		
	Acetachlor	75	10 DAS		
	Oxadiargyl	100	10 DAS		
	Cinmethylin	50–75	7 DAS		
Wetland	Bentazon	2,000	Postemergence	*S. maritimus*	De Datta (1977)
				C. serotinus	Mine et al (1974)
Dryland	Bentazon	1,100	Postemergence	*C. rotundus*	Boswell (1971)
Wetland/dryland	2,4-D	500	6-leaf stage of weed	*S. maritimus/C. rotundus*	De Datta (1983)
	Cyperquat	3,000	Postemergence	*Cyperus* spp.	Akobundu (1978)
Wet-seeded	Propanil	1,000–2,000	6–7 DAS	*S. maritimus*	Vega et al (1971), Paller et al (1971)

[a]DAT = days after transplanting, DAS = days after sowing.

Table 6. Herbicide-resistant sedges associated with rice.

Species	Herbicide to which resistance evolved	Country	References
Cyperus difformis	Bensulfuron	Australia, USA	Graham et al (1994), Pappas-Fader et al (1993)
Fimbristylis miliacea	2,4-D	Malaysia	Watanabe et al (1997)
Scirpus juncoides var. *ohwianus*	Sulfonylureas	Japan	Kohara et al (1999)
S. maritimus	Sulfonylureas	Spain	Valverde et al (2000)
S. macronatus	Bensulfuron, cinosulfuron	Italy	Sattin et al (1999)
	Bensulfuron	USA	Valverde et al (2000)

Source: Valverde et al (2000).

Herbicide resistance

Resistance to herbicides in the weeds of rice is increasing and will probably become more important as more land, especially in Asia, is changed from transplanted to direct-seeded rice. Direct-seeded rice is more dependent on herbicides and increased selection pressure undoubtedly will make resistance more common in weeds associated with rice. Worldwide, 30 weed species associated with rice have evolved resistance to herbicides. The important sedges resistant to different herbicides are presented in Table 6.

Conclusions

Under intensified rice-cropping systems, weeds have become a major constraint to rice farming. Weed species that cause problems in rice vary with agroecological conditions and management practices. Among major weeds of rice, sedges rank second in abundance after grasses. Sedges are the dominant weeds of rainfed rice. In India, continuous use of graminicides in rice has resulted in a shift of weed flora to sedges such as *Cyperus* spp., *Scirpus* spp., and *Fimbristylis* spp. In direct-seeded rice, sedges such as *C. iria* and *C. difformis* are the major problems in both wet- and dry-seeding conditions, whereas *C. rotundus* and *F. dichotoma* are dominant in rainfed uplands. *S. maritimus* is a major problem in lowland rice. Sedges in general are more competitive through underground parts such as rhizomes, tubers, or roots. In rainfed upland conditions, they compete for soil moisture and nutrients, which are the major limiting factors in rainfed areas. With the increased availability of herbicides to control weeds and the concern about water-use efficiency, direct seeding of rice is gaining popularity in all rice-growing countries, including India. Although effective and cheap herbicides are available for the control of grasses and broadleaf weeds in varying rice cultures, the availability of chemicals for the management of various groups of sedges is limited. Considering the diversity of weed problems, no single method of control whether cultural, manual, mechanical, or chemical would be sufficient to provide season-long weed control under all situations. An integrated weed management system as part of an integrated crop management system would be an effective, economical, and eco-friendly approach for management of sedges in rice. The combination of preemergence herbicides with manual or mechanical weeding would be required for effective weed management. Sequential application of pre- and postemergence herbicides and herbicide mixtures may provide broad-spectrum weed control. More research is needed on the ecology of sedges under varying rice culture and their management.

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Weedy rice and its management

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This paper describes the status of weedy rice occurrence, competition losses, and management strategies being adopted by Asian farmers. Review of the literature revealed that weedy rice is an important issue, particularly in direct-seeded rice in all rice-growing areas. Inadequate information is available related to ecological and management aspects of weedy rice. Systematic and concerted efforts are required by scientists and policymakers to tackle this menace. Future priorities related to various subjects pertaining to weedy rice have also been highlighted.

Weedy rice is morphologically and physiologically similar to cultivated rice and belongs to the same genus/species to which cultivated rice belongs. As a result of mutation or natural crosses between cultivated species, weedy characteristics of cultivated rice are developed. Weedy rice matures earlier than cultivated rice and shatters early and easily, and shattered seeds regenerate naturally as weeds. According to Suwanketnikom (2000), weedy rice has become a serious weed in rice fields of more than 50 countries in Africa, Asia, and Latin America. Weedy rice infestation is reported to be increasing with the spread of direct-seeding rice culture in tropical Asia (Moody 1994).

The following characteristics make the rice plant a weedy rice:

- Taller than cultivated rice
- Longer and droopy leaves
- Fewer tillers
- Weak culm
- Long internode
- Plant flowers and grains shatter earlier than in cultivated plant
- Most grains have awns
- Grains have red pericarp
- Grains are smaller

Based on a survey by the Cuu Long Delta Rice Research Institute in Vietnam, red pericarp was considered as the major characteristic of weedy rice (Chin 1997).

Occurrence and competition losses

Review of the literature reveals that weedy rice is a major problem with direct-seeding rice culture. In direct-seeded rice, weedy rice emerges earlier and establishes its roots occupying adequate space and competes well for basic growth resources. Weedy rice competes for nutrients, moisture, and sunlight and by virtue of its taller height and drooping leaves affects photosynthesis. Weedy rice competes strongly with cultivated rice, reducing rice yield, and the prevalence of red grain lowers rice quality. Higher milling costs are incurred to remove the red pericarp, which reduces the percentage of whole rice grain (Austin 1979). The problem of weedy rice has been noticed on account of tillage operations, time and method of rice cultivation, water management, combine harvesting (weedy rice plants are harvested together with the cultivated rice crop and encourage contamination), etc. The emergence rate of weedy rice was higher in fields with no-tillage and rotary-tillage regimes. In a field plowed by rotary-tillage, weedy rice was deeply buried (Choi et al 1995). A study in the United States showed that one red rice plant can produce 1,500 seeds per year (Huey 1978). Preharvest shattering and shedding of weedy rice seeds contaminate harvested rice.

In Vietnam, farmers are aware of the damage brought about by weedy rice. A survey of rice fields revealed that weedy rice occurred mostly in direct seeding (35.5%), followed by wet seeding (32.6%), and transplanting (7.4%). Chin (1997) reported that average yield losses from weedy rice in direct-seeded rice were estimated at 22.5% and 13.8% in Long An and Binh Thuan provinces of Vietnam, respectively.

Weedy rice has not been reported as a weed in China and the probable reason for nonoccurrence was labor-intensive weeding, manual plant selection in the nursery, and transplanting. However, in view of changing cultural practices and labor migration from agriculture to industry, weedy rice may become a problem in the future (Zhang 2000).

In Korea, weedy rice was the most important weed in direct-seeded rice fields (Choi et al 1995). Suh et al (1997) also reported a higher number of weedy rice plants in direct-seeded fields than in transplanted rice fields, with most of the weedy rice found in the hills of cultivated rice and only a few plants grown between hills. However, the number of weedy rice plants occurring in direct-seeded rice fields was higher in rows or between hills than within hills or rows.

In Malaysia, weedy rice was first detected in a Tanfung Korane rice field during 1988 and since then this rice has been found in other areas. This has become a threat to the production of direct-seeded rice in the country, resulting in up to 74% losses in heavily infested rice fields (Watanabe et al 1996, Azmi and Abdullah 1997). Weedy rice was also found to emerge in rice fields through both incorporated shed seeds and contaminated sown seeds.

In Thailand, weedy rice infestations have been observed where direct seeding has been practiced (Vongsaroj 1985). The distribution of weedy rice among farmers is likely to be accomplished by several means, including water, cattle, machinery, and contaminants of new varieties (Chitrakam et al 1995).

Weedy rice does not pose a serious problem in the Philippines because of a greater area under transplanting, but the shift to direct-seeded rice is increasing in some provinces. A majority of the fields where weedy rice was found showed infestation levels of 1% to not more than 30% (Fajardo and Moody 1995). Weedy rice occurs more commonly in fields planted to direct-seeded rice. It does not grow in transplanted rice fields where floodwater is adequate. No study has yet been made to assess the impact of weedy rice infestation on rice yields in the Philippines.

Weedy rice populations were first observed in Sri Lanka in 1997 in Ampara District located in the southeastern part of the country. Weed management has become a problem in direct-seeded rice because of the morphological similarity of weedy rice and cultivated rice.

In Nepal, weedy rice is a problem in rice fields of the hills and *Tarai* belt. Black-husked weedy rice from Kathmandu Valley is prone to shattering. Economic losses from weedy rice have not been estimated so far.

In India, weedy rice has been a problem associated with direct-seeded broadcast rice under dry conditions. However, the problem is not so intense in wet-seeded/transplanted culture. Wild rice/weedy rice has been found to cause significant yield reduction in domestic rice in eastern India.

Weed management

No single method of control can effectively eliminate weedy rice infestation. Azmi et al (1994) and Watanabe et al (1996) opined that successful management of weedy rice requires an integrated approach combining both direct and indirect control measures. The following could be used as important components of integrated weed management, with special reference to weedy rice control:

1. A seed bank of weedy rice may be exhausted by employing deep burial/repeated tillage operations before sowing/transplanting rice. Richharia (1964) recommended direct sowing of pregerminated rice seed on puddled fields, deep plowing to bury wild rice seeds, transplanting rice seedlings in lines for easy identification, and manual removal and changing crop rotation to reduce weedy rice infestation. He also suggested keeping ducks for grazing the seed and seedlings of wild rice.
2. Intensive land preparation (2–3 rounds of tillage) involving blanket or spot sprays with glyphosate or paraquat at low doses has been effective in promoting germination and subsequently killing weedy rice seedlings prior to crop planting. Puckridge et al (1988) demonstrated the effective control of weedy rice through the stale seedbed technique, but this technique could not be followed by farmers because of high costs involved in Thailand.
3. Enhancing the crop seed rate of 80–100 kg ha^{-1} above the optimum of 60 kg ha^{-1} in infested fields has been found advantageous to suppressing weedy rice populations.
4. Replacing direct seeding with wet/transplanted rice to minimize the invasion of weedy rice has been found to be a good choice. Zainal and Azmi (1994) and Azmi and Abdullah (1997) reported that farmers resorting to transplanting rice culture had minimal or no recurrent problem with weeds. In some parts of Vietnam, farmers who had adopted a three-rice cropping system changed to two rice crops and a fallow to permit control of weedy rice. In another part, farmers have succeeded in reducing weedy rice in their fields by introducing transplanted rice culture in one or two cropping seasons after serious infestation in their dry-seeding seasons (Watanabe et al 2000).
5. Sowing of certified seeds (free from weedy rice contamination) is advised in Thailand, Malaysia, the Philippines, and the United States.
6. Roguing of off-types and weedy rice types during tillering, booting, and flowering stages of rice was considered the only available method of controlling weedy rice (Mai et al 2000).
7. Planting of cultivars with distinguishing color to differentiate the crop from weedy forms to enable manual weeding has been found effective in eastern India, where farmers prefer to grow purple-leaf varieties of rice in areas of wild rice/weedy rice problems. This facilitates weeding of weedy rice, which is greenish. The purple-leaf varieties included P-502, R-575, L-12, and C.P. 1 (Gupta 1998). However, these purple leaf varieties were not good yielders and hence purple-stemmed varieties with green foliage were found to

be better (Richharia 1964). The high-yielding purple-stemmed varieties are also limited. One such variety, Kalashree, with a purple base developed at the Central Rice Research Institute, Cuttack (India), and another one, Shymala, developed at the Indira Gandhi Agricultural University, Raipur (India), have been recommended for wild rice–infested areas. However, there is a strong-felt need by the farming community in eastern India for growing purple-base varieties of rice in wild rice–infested areas.

8. Removal of the dropped weedy rice seeds from the ground may help prevent further dissemination.
9. Farmers must be vigilant toward combine harvesters and other farm implements to avoid disseminating weedy seed.
10. Row seeding has been found to be better in terms of increased resistance to lodging, rats, and pests; use of solar radiation for photosynthesis; and controlling weedy rice, as it is much easier to differentiate cultivated rice plants in rows and weedy rice between rows (Luat 1997).
11. Rice in rotation with upland crops is the best integrated method to control weeds and weedy rice (Luat 1996). Well-prepared land before rice sowing and the upland crop rotation in rice-based cropping systems have been recommended by policymakers and scientists in Vietnam to control weeds and weedy rice in rice fields. In the United States, soybean-rice or sorghum-rice rotation systems allow selective chemical control of red rice in the rotation crop to reduce red rice infestation in the subsequent rice crop. Herbicides used to control red rice in soybean include alachlor, metolachlor, metribuzin, or pendimethalin (Khodayari et al 1987). Newer postemergence compounds include imazaquin, imazethapyr, and clethodim (Nastashi et al 1989).
12. Transplanting rice culture, herbicide at land preparation, intensive rototilling before cropping, and manual weeding were considered as effective methods of weedy rice control, mainly by Tanjung Karang farmers in Malaysia.
13. The use of herbicides such as alachlor, butachlor, and molinate can effectively control weedy rice during seedbed preparation in Thailand (Vongsaroj 1976). Weedy rice was found to be completely controlled by thiobencarb (2.1 kg ha^{-1}) and oxadiazon (0.24 kg ha^{-1}) in Korea. Molinate (6.5 kg ha^{-1}), however, gave 26–67% control when applied 6 d before rice seeding (Kuk et al 1997). Chemical control of wild rice was found feasible by protecting the rice seeds from herbicide injury by using antidotes such as 1, 8 naphthalic anhydride (NA) as grain dressing at 0.5–1.0%. Promising herbicides were molinate at 3–4 kg ha^{-1}, alachlor at 1–2 kg ha^{-1}, metolachlor at 0.75 kg ha^{-1}, and thiobencarb at 4.0 kg ha^{-1} (Wirdjahardja and Parker 1977, Parker and Dean 1976). The use of imazaquin-resistant and glufosinate-resistant rice to manage red rice in the United States is the latest finding. However, under Indian conditions, chemical weed control of weedy rice has not been tested on a large scale and hence cultural methods could be adopted. There is currently no available postemergence herbicide that could control weedy rice/red rice selectively in rice because of morphological similarity.

Future priorities

Ishizuka (2000) very rightly expressed his views in a symposium on weedy rice organized in Vietnam that many researchers in Asia have been engaged in studies on wild rice, focusing especially on the history or origin of cultivated rice, and comparative studies between cultivars of domesticated rice and lines of wild rice, mainly to enhance our understanding of cultivated rice. Since weedy rice is a serious threat in direct-seeding culture and farmers are resorting to direct seeding in place of transplanting because of the shortage of labor, water, and power in South and Southeast Asia, weed scientists need to concentrate their efforts on the following:

1. Information on weedy rice–infested areas, the magnitude of infestations, estimations of losses, and determining economic threshold level are required, especially under direct-seeded rice.
2. Research work on weedy rice germination in relation to temperature, moisture, soil types, and its dormancy and longevity should be undertaken. Technology for weedy rice seed bank management could be developed.
3. Long-term field studies could begin at a permanent site in cropping systems involving direct-seeded rice to monitor the changes in weedy rice infestations influenced by tillage and agronomic practices.
4. No effective postemergence herbicide has been developed for selective control of weedy rice in cultivated rice. The herbicide industry should think in this direction.
5. Breeders are required to develop high-yielding varieties differing in color and morphological traits to enable easy identification for manual weeding.
6. Crop rotation will certainly play a significant role in checking the infestation of weedy rice in cultivated rice. Profitable and effective crop rotations could be developed keeping in view the local needs of farmers and agronomic situations prevailing in different agroclimatic zones, which could minimize the infestation of weedy rice without reducing yield and income.
7. Testing of implements and tools could be a good alternative in controlling weedy rice. Proper testing of implements could be done for different ecological situations.
8. An effective, feasible, and cost-effective integrated weed management approach with special reference to weedy rice management involving good land preparation/stale seedbed technique, seed bank management, proper removal of weedy rice/off-type plants before flowering, and crop rotation are required for the emerging needs of rice growers.
9. In general, I suggest enhancing awareness among farmers in relation to the emerging problems of weedy rice and its effective management. Regulations pertaining to weedy rice seed contamination in rice could be enforced by government authorities and seed-producer agencies to prevent this menace.

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Weed species shifts in response to direct seeding in rice

V.P. Singh, G. Singh, Y. Singh, M. Mortimer, and D.E. Johnson

Weed populations in rice change in response to crop management. Changes in habitat favor certain species already present or may allow the entry of alien species, and these will flourish where weed management is inadequate. Further, repeated application of certain control practices may lead to an evolutionary response such as the development of herbicide resistance. Knowledge of these changes in response to crop management can help to predict likely changes elsewhere. At Pantnagar, studies comparing crop establishment and weed management options over a 4-year period have shown that changing from transplanting to direct seeding resulted in marked changes in weed populations in the rice-wheat system. In general, with direct seeding, three annual grasses, *Echinochloa crus-galli, E. colona,* and *Leptochloa chinensis*, the perennial sedge *Cyperus rotundus*, and certain broadleaf weeds such as *Commelina diffusa* and *Caesulia axillaris* increased. Species responded differently, however, to the various options. *C. rotundus* decreased with wet seeding, whereas, in contrast, *C. axillaris* decreased with dry seeding. The establishment method of the wheat crop also influenced the weeds occurring in the subsequent rice crop as, for example, *E. colona* infestation was reduced by zero-tillage as compared with conventional tillage. A significant step toward improved weed management approaches for direct-seeded systems in rice-wheat will be the synthesis of such findings, along with the development of decision frameworks and information sources to enable farmers and extension staff to improve their decision making.

Changes in crop management are likely to result in altered composition of the weed flora (Mortimer 1990). The three main means by which a species becomes incorporated into the weed flora are preadaptation, evolution, and immigration, of which the former is probably the most common means by which new weed infestations occur. In this way, species present in an agroecosystem are favored by changes in crop management practices and, as a result, gain in importance in the weed community. Such changes in weed species composition have been observed in Asia when transplanting is replaced by direct seeding (Azmi and Baki 2003, Ho 1998). The changes that result from a shift to direct seeding in the rice-wheat system of India have not been reported, however, and this is a significant gap in our knowledge relating to the sustainability of this proposed system.

Weed species composition in the rice-wheat system in India

A field experiment to compare the effects of different rice and wheat establishment practices and related weed control measures was established at G.B. Pant University of Agriculture and Technology, Pantnagar. This experiment was established in 2001 and rice and wheat crops were grown alternately through to 2005. The rice establishment methods comprised transplanting, wet seeding (pregerminated seed sown after puddling), dry drill-seeded (after conventional tillage), dry drill-seeded (after conventional tillage, a flush irrigation, and an application of glyphosate), and dry-seeded zero-tillage. Wheat followed the rice harvest and it was sown after either zero-tillage or conventional dry cultivation (see V.P. Singh et al, this volume, for experimental details).

Weed species were recorded by biomass and number at 28, 56, and 84 days after seeding and at harvest. This experiment had 14 principal weed species over the four cropping seasons: the broadleafs *Caesulia axillaris, Commelina diffusa, Cynotis axillaris*; the sedges *Cyperus difformis, C. iria, C. rotundus,* and *Fimbristylis miliacea*; and the grasses *Echinochloa colona, E. crus-galli, Eragrostis japonica, Ischaemum rugosum, Leptochloa chinensis*, and *Paspalum distichum.*

Major shifts in the composition of the weed flora occurred over 2000-02 in response to rice crop establishment methods (Singh et al 2003). With direct seeding, in general, there was an increase in annual grasses *E. crus-galli*, *E. colona*, and *L. chinensis*, the perennial sedge *C. rotundus*, and certain broadleaf weeds such as *C. diffusa* and *Caesulia axillaris.* Significant seasonal variation (P <0.01) in weed density occurred from 2002 to 2004. Figure 1 illustrates the rates of change in abundance comparing densities present in 2002 with those in 2004 at 28 DAS/DAT for the most abundant species in 2002. With the exception of *C. diffusa*, all the weed populations declined over this time period. In contrast, by 2004, *I. rugosum*, *C. iria*, *L. chinensis*, *E. crus-galli*, and *Cynotis axillaris* had become incorporated into the flora and were recorded at 28 DAS/DAT.

Figure 2 shows the density of weeds present at 56 DAS/28 DAT in 2004. The differential response of species to rice establishment method was highly significant (P<0.01) in all cases in unweeded plots. Significant changes (P<0.05) in weed density in response to establishment after one hand weeding were evident only for *C. rotundus, E. colona*, and *I. rugosum*. These species and *Cynotis axillaris* were also found after herbicide + hand weeding in dry-seeded rice, dry drill-seeded plots that had experienced flush irrigation, or the zero-tillage plots.

Three species were identified as major threats to rice use with sequential use of the same crop establishment method: *E. colona* in drill-seeded and zero-till rice, *I. rugosum* in wet seeding, and *C. rotundus* in drill seeding and zero-tillage. *E. crus-galli* and *L. chinensis*, although present in unweeded plots and after a single hand weeding, were effectively controlled by postemergence herbicides.

Influence of crop establishment method

Comparison of the weed flora in unweeded plots after four seasons (2001-04) indicated that cultivation practices associated with both rice and wheat crop establishment methods affected the weed flora emerging in the rice crop. The responses of selected major species to these cultivation practices are qualitatively summarized in Table 1. *C. iria* did not respond to establishment methods in either crop, whereas *C. rotundus* increased in abundance under zero-tillage. *E. colona* densities were highest in zero-tilled rice plots that had been conventionally tilled for wheat with conventional tillage in wheat also increasing the abundance of *I. rugosum* in rice. Conventional tillage for wheat, however, resulted in lower abundance of *Caesulia axillaris*. Wet seeding in rice increased the densities of *F. miliacea*, *I. rugosum*, and *Caesulia axillaris.* The mechanistic processes underlying these changes require further research, but a plausible hypothesis is that seed persistence is a function of seed size and the large-seeded grasses are more likely to survive in the seed bank when

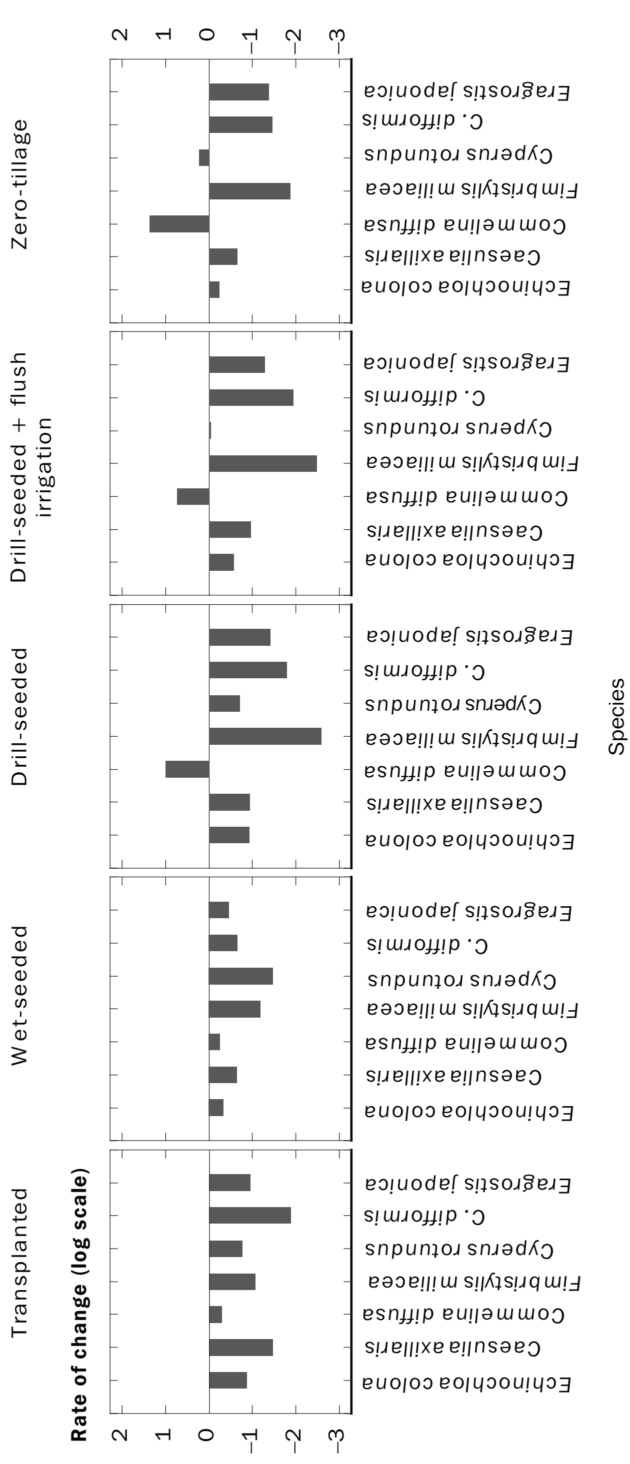

Fig. 1. Changes in abundance (mean density at 28 DAS/DAT) of weeds according to rice establishment method for species recorded in 2002. Data are the logarithm of the ratio of densities in 2004 to 2002, Pantnagar.

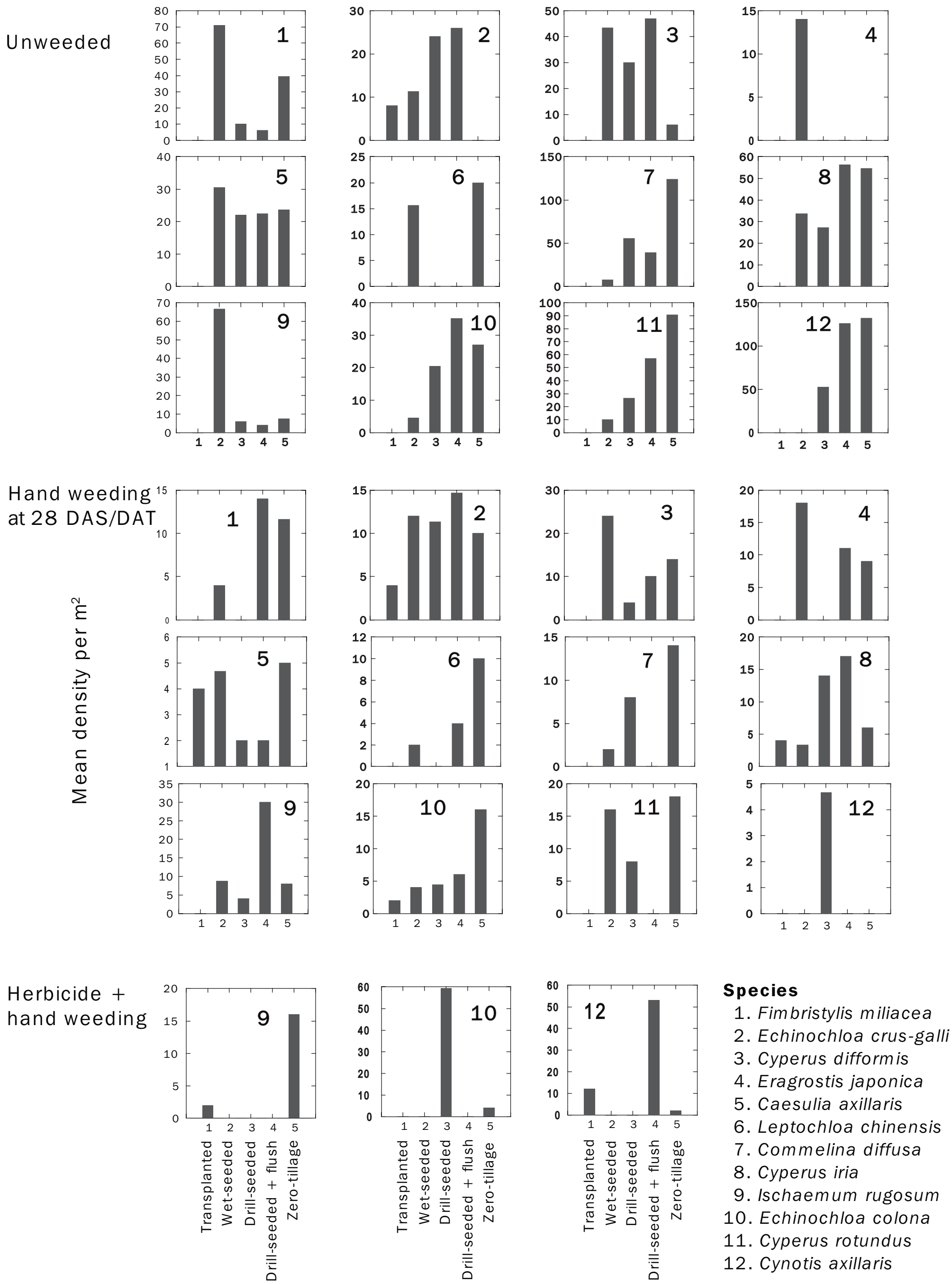

Fig. 2. Density of weeds present at 56 DAS/28 DAT in 2004 in response to rice crop establishment and weed management.

Table 1. The influence of rice and wheat crop establishment methods on abundance (plant density, 28 DAS/DAT) of selected weed species in rice, Pantnagar. Differences of up to threefold in mean density are reflected in the abundance range (low to high) for each species.

Species	Response to rice establishment method[a]	Abundance[b, c]		Response to wheat establishment method	Abundance[c]	
		Low	High		Low	High
Caesulia axillaris	Y	DS/ZT	WS	Y	Conv.	ZT
Commelina diffusa	Y	WS	ZT	–	–	–
Echinochloa colona	Y	WS	ZT	Y	ZT	Conv.
E. crus-galli	–	–	–	–	–	–
Ischaemum rugosum	Y	ZT	WS	Y	ZT	Conv.
Fimbristylis miliacea	Y	DS	WS	–	–	–
Cyperus iria	–	–	–	–	–	–
C. rotundus	Y	WS	ZT	Y	Conv	ZT

[a]Y = significant effect ($P < 0.05$) of establishment method from analysis of variance. – = not significant. [b]Rice establishment methods: DS = dry-seeded, WS = wet-seeded, ZT = zero-tillage. Wheat establishment methods: Conv. = conventional tillage, ZT = zero-tillage. [c]Abundance estimate (low/high) based on the density of plants at 28 DAS/DAT in unweeded rice plots in 2004.

buried through conventional tillage of wheat, whereas exposure on the surface under ZT systems enhances mortality rates.

Influence of herbicide and manual weeding

Table 2 indicates the species that made different relative contributions to the total weed pressure according to rice crop establishment method. At 28 DAS, higher densities of *Echinochloa crus-galli* in wet-seeded and ZT rice were associated with ZT wheat. *I. rugosum* in wet-seeded rice and *E. colona* in drill-seeded rice were reduced by ZT wheat.

Weed population densities after hand weeding reflected emergence after 28 DAS and escapes from manual weed control. In the drill-seeded and ZT rice, the impact of ZT in wheat was to reduce the overall density of weeds present at 56 DAS. By implication, ZT of wheat will reduce weed density in rice, requiring removal by hand weeding after herbicide application. With wet seeding, the characteristic late emergence of *I. rugosum* was very apparent, suggesting the need for late postemergence intervention to control this weed.

Discussion

These results illustrate some of the likely impacts on weed species composition due to changes in rice and wheat establishment practices. The mechanistic processes behind these changes are not identified but the effects of burial and soil and water conditions early in crop growth will reflect upon weed seedling recruitment. These studies indicate the likely responses of individual weed species to management practices and this, in turn, suggests possible "trajectories" that weed communities will follow due to changes in crop establishment methods. As a management tool, this information can be used to identify establishment practices that will "disadvantage" certain weeds and thus prevent undesirable changes in the weed community. Using weed ecology in this way is "knowledge-intensive" yet it may manifest itself only as a greater emphasis on rotations of crop management practices. As an example, a buildup of *I. rugosum* in wet-seeded rice may be discour-

Table 2. Mean density (plants m^{-2}) of grass weeds present before hand weeding at 28 DAS/0 DAT and at 56 DAS/28 DAT after hand weeding at 28 DAS/DAT, 2004, Pantnagar. For each species, the interaction of wheat × rice crop establishment method was significant (P <0.05).

Species	Wheat establishment[a]	Rice establishment			
		Transplanted	Wet-seeded	Drill-seeded	Zero-tillage
Before hand weeding at 28 DAS/0 DAT					
Echinochloa colona	CTW	0.0	4.5	17.8	18.3
	ZTW	0.0	1.8	5.5	22.2
E. crus-galli	CTW	0.0	2.0	8.5	0.0
	ZTW	0.0	10.7	10.0	14.0
Ischaemum rugosum	CTW	0.0	13.2	3.7	0.0
	ZTW	0.0	4.5	3.8	1.2
Total	CTW	0.0	19.7	30.0	18.3
	ZTW	0.0	17.0	19.3	37.3
At 56 DAS/28 DAT after hand weeding at 28 DAS/0 DAT					
Echinochloa colona	CTW	0.0	1.7	7.7	8.8
	ZTW	0.3	1.3	4.3	10.5
E. crus-galli	CTW	0.7	1.0	4.8	3.3
	ZTW	0.3	2.8	2.0	0.8
Ischaemum rugosum	CTW	0.0	21.2	0.8	1.0
	ZTW	0.2	19.8	0.5	4.2
Total	CTW	0.7	23.9	13.3	12.7
	ZTW	0.9	24.0	6.8	6.5

[a]CTW = conventional tillage for wheat; ZTW = zero tillage for wheat.

aged by using zero-tillage in either the rice or the wheat. In time, the repeated use of ZT for rice may lead to greater densities of *E. colona*, which could then be discouraged by shifting back to wet-seeded rice. With increasing cropping intensity and constraints to increased reliance on herbicides, greater emphasis on weed ecology could enable more effective weed control strategies. A significant step toward improved weed management systems for direct-seeded rice in the rice-wheat system will be the synthesis of such findings, and the development of decision frameworks and information sources to enable farmers and extension staff to improve their decision making (see also Johnson and Mortimer, this volume).

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Development issues

Issues for weed management in direct-seeded rice and the development of decision-support frameworks[1]

D.E. Johnson and A.M. Mortimer

Changes in the production environment, increasing costs, and decreasing availability of labor and water are leading farmers to consider alternative management options. Direct seeding is a viable alternative to transplanting provided weeds are adequately managed, but weed management for direct-seeded rice is inherently "knowledge-intensive." Weed population shifts are a likely result of a change in establishment practices for direct seeding, and experience elsewhere suggests that changing weed problems will challenge management. To respond to these changes, farmers/extension need increased amounts of information on a range of issues in order to improve and aid decision-making. Information is necessary at different scales from the regional to farm level for both policy and technical decision-making. The information can be integrated in the form of decision-support frameworks. These comprise information describing current cropping practices and comparative assessments of technology options. They then provide guidance on the choice of options in the form of decision trees.

Rice production over much of India has been transformed, with the harvest increased from 98 to 134 million t from 1985 to 2000 (IRRI 2004) through the introduction of improved germplasm, agronomy, pest management, and mechanization. In the 1960s, India imported up to 1 million t annually to meet its domestic demand, though by the late 1970s India was self-sufficient. In particular, the traditional wheat-growing states of Punjab, Haryana, and Uttar Pradesh have had substantial increases in production. In Punjab, production increased from 0.9 to 13.1 million t and in Uttar Pradesh from 4.4 to 19.4 million t from 1968 to 1999. Favorable irrigation infrastructure has made these increases possible. India's rice-growing environments are extremely diverse, however, and similar production increases have not occurred in the states of eastern India, where a large unmet demand for rice remains.

Along with germplasm development and increased use of fertilizer, weed management practices have changed. Declining availability of labor for agriculture in some areas and increasing labor costs have required farmers to seek alternatives to manual weeding, which has long provided farmers with the means to limit losses to weeds. Herbicide use has allowed a massive release of

[1]Adapted from a paper presented at the World Rice Research Conference, Rice is life: scientific perspectives for the 21st century, Tsukuba, Japan, November 2004.

labor from agriculture that is expected to continue. The use of herbicides, however, as elsewhere in the world, has been accompanied by concerns over the evolution of herbicide resistance in weeds, weed species population shifts, and concerns about the environment. In addition to labor, concerns are increasing over future supplies of irrigation water. Farmers in many rice-growing areas are likely to have only limited availability of irrigation water and, in the future, most of the 22 million ha of dry-season rice in South and Southeast Asia will fall into an "economic water scarcity zone" (Bouman and Tuong 2003). Water scarcity threatens the sustainability of irrigated rice ecosystems since it may no longer be feasible for farmers to undertake wet cultivation and flood in fields to ensure good crop establishment and control weeds. The development and adoption of alternative irrigation strategies such as "alternate wetting and drying" and "aerobic rice" may enable good crop growth but the lack of sustained flooding will greatly increase potential losses from weeds. These systems may integrate direct seeding and herbicide use, yet, to be sustainable, effective weed management strategies are required.

In many areas of Asia, including Malaysia and Vietnam, transplanting of rice is being replaced by direct seeding as farmers respond to increased costs or decreased availability of labor or water (Pandey and Velasco 2005). Direct-seeded systems are less robust than transplanting as elements of soil moisture, irrigation, drainage, and weed control are more critical to successful crop establishment and growth. With management playing a more decisive role in crop establishment and weed control, as a practice, direct seeding can be described as being "knowledge-intensive."

The technical constraints and economic demands are leading to change in production systems and are causing farmers to be increasingly dependent on information from outside sources. We discuss below some issues related to direct seeding, its adoption, and weedy rice and herbicide resistance, for which farmers could benefit from having a greater availability of current knowledge.

Weed management issues related to direct seeding

As described above, weed management is one of the major constraints to direct seeding. Studies in the rice-wheat system in India, and in Bangladesh (V.P. Singh et al, Mortimer et al, this volume), have established a substantial knowledge base on weed management in some of the most productive rice systems in Asia. These systems have commonality in many of the weed species present but also reflect a continuum from transplanting to direct seeding. Four pertinent observations from this database can be made.

First, variability is considerable in soil type, irrigation, and drainage, and at the farm level because of resources and cropping practices that affect the selection of direct-seeding options. Second, associated with direct seeding is an inevitable shift in the weed flora toward competitive grasses, including *Echinochloa* species, *Leptochloa chinensis,* and *Ischaemum rugosum* in wet-seeded rice, and in dry-seeded rice the perennial sedge *Cyperus rotundus*. Management of such weeds requires farmers to have the ability to anticipate changes in weed populations and, to reduce losses, exploit integrated strategies comprising tillage, water, and crop management to complement herbicide application.

Third, "weedy" rice (*Oryza sativa*) has become a relatively recent problem in Southeast Asia although "red" rice has been known in Latin America for decades. In the late 1980s, weedy rice was observed in direct-seeded rice of Malaysia and by the mid-1990s several of the major rice production schemes had infested areas (Azmi et al 2005). In the Philippines, weedy rice was reported in 1990, and in Vietnam in 1994, and it is now widespread in the central region of Thailand. Its vigorous growth results in serious yield losses, and its rapid spread makes it a considerable threat to direct-seeded rice production. Control strategies combining preventive and cultural measures, however, have been shown to be effective. Prevention is one of the immediate steps that should be implemented in many countries. This may involve sensitizing farmers to risks, closer inspection of seeds, and roguing at the initial appearance of weedy rice in fields.

Finally, intensive herbicide use in rice has resulted in certain weed species, including *Sphenoclea zeylanica* and *Fimbristylis miliacea,* developing resistance to 2,4-D herbicide (Watanabe et al 1997). Lately, possible ALS (acetolactate-synthase) inhibitor-resistant biotypes of *Bacopa rotundifolia* and *Limnophila erecta* have been reported (Azmi and Baki 2003). The risks of herbicide resistance evolving are known and strategies exist to mitigate the risks of occurrence. What is required is a greater awareness within farm communities of the resistance problem and suitable management strategies.

Information needs for improved weed management systems

As argued elsewhere in this volume by various authors, the transition from traditional transplanting to direct seeding is knowledge-intensive and renders ineffective the experience of traditional rice production systems with their reliance on indigenous knowledge and manual inputs (often where opportunity costs of labor are discounted). Information must be acquired from external agencies and uncertainty is often involved over the reliability of information and the implementation of actions. Decision rules or heuristics (see Heong and Escalada 1997 for discussion) may address this difficulty but, to be successful, must focus appropriately and in context.

Table 1 categorizes the issues that must be examined in a decision-support framework for weed management in direct-seeded rice. Since decision-support frameworks may apply at different scales (regional, production system in locality, and individual farms) and have multiple target audiences (policymakers, researchers and extension, and farmers), it is important to delineate the context with respect to production systems.

Characterization of the existing cropping system(s) through constraint analyses enables identification of the magnitude and variance of yield gaps caused by the presence of weeds. In direct-seeded rice, these may be large (typically 10–50% of attainable yield) and are often a consequence of an inability to implement timely weeding (20–30 days after sowing), which in turn may reflect difficulties in water management (irrigation and drainage), land leveling, and appropriate water management for selected herbicides. Constraints in credit, knowledge, and resources at the farm level contribute to poor agronomic practices. Characterization studies in weed management typically involve on-farm trials comparing yields from plots with intensive weed management as opposed to farmers' practices, coupled with focus-group interviews to describe farmer decision-making in weed management and to explore perceptions and the availability or lack of information.

Comparative technology evaluation provides a partial budgeting analysis of system components and identifies intervention points for change. Typically, and at its simplest, a matrix of components versus systems is constructed and subjected to sensitivity analysis by partial budgeting. Pandey and Velasco (2002) have pointed to the likelihood of trade-offs. For instance, the introduction of direct seeding may have a negative impact on labor demand for the adoption of direct seeding in place of transplanting or a positive effect where it allows for cropping intensification, both of which may have policy implications (Pandey and Velasco 2002). Likewise, improvements in water-use efficiency may be achievable only by a switch in herbicide product (e.g., butachlor to pretilachlor), which reduces the spectrum of control and necessitates more costs in later manual weeding.

As a third framework component, *decision trees* provide farm-level information in the form of structured questions that enable answers in the form of options to be chosen. These trees specifi-

Table 1. Issues for consideration in a decision-support framework on options for direct seeding and weed management (adapted from Johnson and Mortimer 2005).

Domain	Focus		
	Policy advisor	Extension	Farmer
Socioeconomic	Implication of changes for establishment of weed management practices: ● Herbicide use ● Displacement of labor ● Patterns of land and water use ● Farm productivity ● Public/ private partnerships	Cost-benefit analysis of component technologies and system profitability	Choice of weed management methods in relation to ● Labor ● Knowledge ● Resource availability ● Input costs.
Biophysical characteristics of production systems	● Yield potential ● Yield gaps because of weeds ● Stability of rice-based cropping systems ● Diversification of cropping systems ● Crop establishment methods	● Integration of weed management technologies, agronomic practices, and cultivar selection ● Prevention of herbicide resistance ● Preventive methods to prohibit weed species shifts ● Environmental protection	Weed management options in relation to cropping systems, site location, water management, and other agronomic variables
Weed management technologies	Choice of mechanical/ chemical control	Information on individual component technologies	Information on ● Target weed species ● Herbicide use ● Timing of application

cally focus on technical issues related to the adoption of a particular system component and are most effective when heuristics are employed. The question "*Are weeds that emerge early in the life of a rice crop the only ones to contribute to yield loss?*" may initiate a tree that can lead to the recognition of the risk of intransigent weeds that in practice require identification skills in scouting rice fields. For a farmer in the irrigated environment, the question "*What are my options for rice establishment*?" might initiate a tree involving several steps and covering the range of direct-seeding options (see Fig. 1 for an example). Farmers with limited access to irrigation might have more limited options and the choice might be between transplanted rice and dry direct seeding. Wet-seeded rice will necessitate a higher degree of water management.

Conclusions

Traditional and modern rice systems alike are complex, the management often sophisticated, and substantial information is required to enable farmers to judge objectively what the best technology options are. This is certainly true in the transition to direct seeding and the management of intractable weed problems. Gaining access to such information may present a major obstacle for

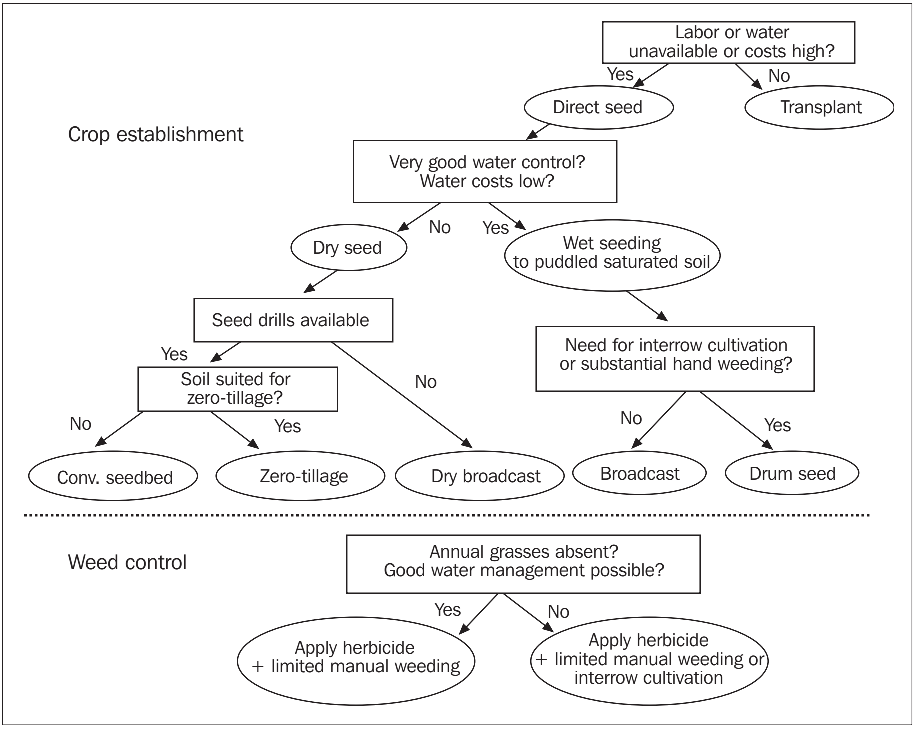

Fig. 1. Illustrative decision tree for adoption of direct seeding with respect to irrigated rice in the rice-wheat system, India.

potential adopters. The challenge for researchers is to adequately examine the variability of rice-farming systems for which they are making recommendations and to synthesize the results in ways that will make the conclusions available to those who will use them. Only in this way will farmers obtain benefit from advances in technology and be able to meet the challenges of a changing production environment.

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Notes

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The economics of direct-seeded rice in eastern India

S.P. Singh, A. Orr, Shailendra Singh,[1] and G. Singh

The private costs and benefits of dry-seeded rice (DSR) were investigated using data from on-station trials at Pantnagar, Uttaranchal, for 2002 and 2003. Results showed that DSR was profitable for farmers, giving net returns of Rs. 13,350 per ha for dry-seeded rice and Rs. 11,592 per ha for wet-seeded rice compared with Rs. 10,343 per ha for transplanted rice. Net labor savings with DSR averaged 27 days per ha. A provisional cost-benefit analysis suggests that DSR was also profitable nationally. Transplanted rice was as socially profitable as DSR only if (1) labor was assumed to have zero opportunity cost, (2) yields were halved, or (3) environmental and health-related costs were twice as high as private costs. DSR was also profitable according to the compensation principle of welfare economics. However, these analyses did not take into account equity issues. DSR reduces equity because it transfers income from labor to farmers without a compensating increase in output. Gender segmentation in the labor market and the absence of alternative employment at the local level impose additional social costs.

Rice and wheat are the two major cereal crops in India occupying nearly 44 million and 26 million ha, with an annual production of 90 million and 73 million tons, respectively. In the states of Uttar Pradesh and Uttaranchal, rice and wheat cover nearly 6 million and 9.3 million ha, with annual production of 11.3 million and 23.5 million tons, respectively. Of the total cultivated area in the *kharif* season, 43% is under rice, whereas wheat covers 67% of the total cultivated area in the *rabi* season. In most rice fields, the succeeding crop is wheat, making rice-wheat the most important crop sequence in these states.

There are three principal methods of rice establishment: dry seeding, wet seeding, and transplanting. Dry seeding consists of sowing dry seeds on dry (unsaturated) soil. Seeds can be broadcast, drilled, or dibbled. Wet seeding involves sowing pregerminated seeds on wet (saturated) puddled soil. Transplanting involves replanting of rice seedlings grown in nurseries in puddled soil. Because the seeds are sown directly, the dry- and wet-seeding methods are often referred to jointly as direct seeding.

[1]Part of the data presented in this paper come from the Ph.D. (agronomy) thesis of Shailendra Singh.

Although transplanting has been a major traditional method of rice establishment in Asia, economic factors and recent changes in rice production technology have improved the desirability of direct-seeding methods. Rising labor costs and the need to intensify rice production through double and triple cropping provided the economic incentives for a switch to direct seeding. Simultaneously, the availability of high-yielding short-duration varieties and chemical weed control methods made this switch technically viable. As the rice production systems of Asia undergo adjustments in response to the rising scarcity of land, water, and labor, a major adjustment can be expected in the method of rice establishment.

Technology that benefits farmers may not be desirable in terms of economic efficiency or in terms of equity. Cost-benefit analysis is required to measure the real cost of resources to the economy as a whole. In addition, new technology that displaces labor without any increase in output may not be compatible with social objectives such as poverty alleviation. In India, where the livelihoods of many poor people depend on wage employment in agriculture, this issue cannot be ignored. A social cost-benefit analysis that addresses the distribution of costs and benefits must take equity into account. This is a complex exercise that is not attempted here; the analysis is restricted to questions of economic efficiency.

This paper aims to provide an overview of economic issues relevant for changes in crop establishment methods. The specific objectives are to

1. Compare costs and returns under different rice establishment methods in the rice-wheat cropping system,
2. Compare activity-wise labor requirements under different rice establishment methods, and
3. Estimate the private costs and benefits of different rice establishment methods.

Advantages and disadvantages of direct seeding

Direct-seeding methods have several advantages over transplanting. First, direct seeding saves labor. Depending on the nature of the production system, direct seeding can reduce the labor requirement by as much as 50%. Second, in situations in which no substantial reduction in labor requirement occurs, direct seeding can still be beneficial because the demand for labor is spread out over a longer time than with transplanting, which needs to be completed within a short time. The traditional dry-seeding system (*beushani*) in rainfed areas of eastern India is a good example. Land preparation, laddering, and weeding operations in this system are spread over several months, thus allowing farmers to make full use of family labor and to avoid labor bottlenecks.

Third, when rainfall at planting time is highly variable, direct seeding may help reduce the production risk. The traditional system of direct (dry) seeding in some rainfed tracts of eastern India evolved partly in response to rainfall uncertainty (Fujisaka et al 1993). Direct seeding can also reduce the risk by avoiding terminal drought that lowers the yield of transplanted rice, especially if the latter is established late because of delayed rainfall. Fourth, direct seeding can facilitate crop intensification. In Iloilo, Philippines, the spread of direct seeding in the late 1970s led to double-rice cropping in areas where farmers previously grew only one crop of transplanted rice (Pandey and Velasco 1998). Similarly, in the Mekong Delta, cropping intensity increased rapidly over the past decade as farmers switched to direct-seeding methods (Bo and Min 1995). Finally, irrigation water use can be reduced if direct-seeded (especially dry-seeded) rice (DSR) can be established earlier by using premonsoon showers. In the Muda Irrigation Area of Malaysia, farmers have been able to establish successful rice crops by dry seeding when the irrigation water supply was low (Ho 1994). Similarly, water use in wet-seeded rice in the Philippines has been substantially lower than in transplanted rice (Bhuiyan and Khan 1995).

Direct seeding also has several potential disadvantages, however. The yield of direct-seeded rice under farmers' field conditions tends to be lower than that of transplanted rice (TPR). Poor and uneven establishment and inadequate weed control are the major reasons for its poor performance (De Datta 1986). Farmers may end up using most of the labor saved by direct seeding to control weeds. In addition, the chemical cost of weed control tends to be higher than in transplanted rice. Farm survey data from Iloilo indicated that the cost of weed control for DSR was as high as 20% of the total preharvest cost (Pandey and Velasco 1998). Greater use of chemical weed control in DSR can also be potentially damaging to human health and the environment. Other major problems with DSR include difficulties in controlling snails and quality deterioration resulting from harvest that may occur during the rainy season.

Nearly 21 million ha, 44% of the rice area in India, are rainfed and even the area under irrigation faces an uncertain power supply during critical periods of the crop cycle. Timely transplanting is difficult because of unstable rainfall and transplanted rice suffers from drought when rainfall after establishment is insufficient for cultivation. Farmers' choice of crops, crop establishment, and adoption of new technology is governed by many personal, institutional, economic, and social considerations. Major issues that need in-depth study in the rice-wheat cropping system are the low productivity of wheat in rice fields, the stability of high rice yields, efficient resource use/energy conservation, better cropping sequences, and concern about the increasing weed population.

Methods

Costs and returns

Primary data for this paper are based on on-station trials at Pantnagar (Singh 2004). In all, 12 treatment combinations were arranged in a split-plot design with three replications. The main plot consisted of three rice establishment methods (dry seeding in unpuddled soil, wet seeding in puddled soil, and transplanting in puddled soil) whereas subplots consisted of two levels of weed control practices (herbicide + two hand weedings and unweeded). During the *rabi* season, wheat was sown as a subplot treatment as zero-tillage and conventional tillage. Each plot where rice was sown in the *kharif* season was divided into two parts, half of which was prepared with conventional tillage and the rest sown with zero-tillage.

Different herbicides were applied in the three rice establishment methods. In dry-seeded rice, pendimethalin at 1 kg ha^{-1} was applied as a spray in 600 liters of water 2 days after sowing, followed by hand weeding at 30 and 60 days. In wet-seeded rice, cyhalofopbutyl at 100 g ha^{-1} was applied as a spray in 600 L of water 15 days after sowing, followed by hand weeding after 30 and 60 days. In transplanted rice, butachlor at 1.5 kg ha^{-1} was applied by mixing with urea 3 days after transplanting, followed by hand weeding at 30 and 60 days. Costs and returns were based on the existing prices then. The total cost of production of each treatment was calculated by adding common operating costs to the cost of each treatment. Net income was calculated to assess the economics of rice-wheat with various treatments.

Cost-benefit analysis

Private and public costs and benefits diverge when market prices do not reflect the real opportunity cost of resources. In countries with widespread underemployment, for example, the market wage rate does not reflect the opportunity cost of labor since labor may not have an alternative use. New technology should then be evaluated using "shadow prices" that represent the real economic cost of resources.

An economic or social cost-benefit analysis of direct-seeded rice with herbicides would have to include the costs of

- *Externalities*, such as possible damage to the environment through pollution, potential revenue losses from damage to fish stocks, and damage to human health caused by inappropriate methods of application or contamination through the food chain. DSR may also have positive externalities by reducing environmental damage through methane emissions and groundwater depletion (Grace et al 2003).
- *User costs*, or the discounted value of foregone future revenues due to environmental damage caused by herbicides.
- *Labor displacement*, particularly in India, where market wage rates do not reflect the real opportunity cost of labor and alternative employment opportunities for displaced workers may not be available.

The absence of information on these costs makes it impossible to measure the net economic costs of direct-seeded rice and herbicides with precision. Following Naylor (1994), however, it *is* possible to provide some provisional answers by asking three questions:

- How much would variable costs have to rise (reflecting externalities) for the benefit-cost ratio of herbicides/direct seeding to equal that of transplanting?
- How much would yields have to fall (reflecting user costs) for the benefit-cost ratio of herbicides/direct seeding to equal that of transplanting?
- How much would labor wages have to fall (reflecting the economic cost of labor) for the benefit-cost ratio of herbicides/direct seeding to equal that of transplanting?

Results

Rice

Costs and returns show substantial variation between methods of crop establishment (Table 1). The treatment cost of dry-seeded rice was Rs. 9,423 ha^{-1} against Rs. 11,893 ha^{-1} in wet-seeded rice and Rs. 12,105 ha^{-1} in transplanted rice. This indicates that the cost of transplanted rice is higher by Rs. 2,682 ha^{-1} than that of dry-seeded rice and the cost of wet-seeded rice is higher by Rs. 2,470 ha^{-1} than that of dry-seeded rice. The major activities accounting for the cost savings in dry-seeded rice over transplanted rice were land preparation (Rs. 1,680 ha^{-1}), sowing nursery/transplanting (Rs. 3,157 ha^{-1}), and irrigation (Rs. 686 ha^{-1}) (Fig. 1). However, weed management was higher by Rs. 2,601 ha^{-1} than with transplanted rice. Seed expenditure was higher in dry-seeded rice by Rs. 240 ha^{-1} over transplanted rice, although it was less than the seed cost of wet-seeded rice. Since no difference was found in the main grain yield, there was no substantial difference in gross returns. Net returns over total cost were highest in dry-seeded rice (Rs. 13,350 ha^{-1}) followed by wet-seeded rice (Rs. 11,592 ha^{-1}) and transplanted rice (Rs. 10,343 ha^{-1}) (Fig. 2).

Wheat

Table 2 and Figure 3 show the costs and returns of a wheat crop after three rice establishment methods with conventional tillage and zero-tillage for two years. The cost of wheat cultivation after dry-seeded rice was lower than in conventional tillage by Rs. 1,128 ha^{-1} in 2002-03 and lower by Rs. 1,122 ha^{-1} in 2003-04. Net returns of wheat in dry-seeded rice remained higher in both years. This indicates that, with proper management, the decline in wheat yield after rice could be effectively arrested.

Table 1. Costs and returns under different establishment in rice-wheat systems mean of 2002 and 2003).[a]

Activities	Treatments: Dry-seeded rice	Treatments: Wet-seeded rice	Treatments: Transplanted rice	Difference of dry-seeded rice over: Wet-seeded rice	Difference of dry-seeded rice over: Transplanted rice
Land preparation	2,826	4,506	4,506	–1,680	–1,680
Seed	1,200	1,680	960	–480	+ 240
Sowing/transplanting/nursery	640	1,014	3,797	–374	–3,157
Irrigation	1,116	1,790	1,802	–674	–686
Weed management	3,641	2,903	1,040	+ 738	+ 2,601
Total treatment cost	9,423	11,893	12,105	–2,470	–2,682
Common operating costs	10,364	10,364	10,364	0	0
Total costs	19,787	22,257	22,469	–2,470	–2,682
Gross returns	33,137	33,849	32,812	No substantial difference	
Net returns over total costs	13,350	11,592	10,343	+ 1,758	+ 3,007

[a]In Rs. ha^{-1}.
Source: Singh (2004).

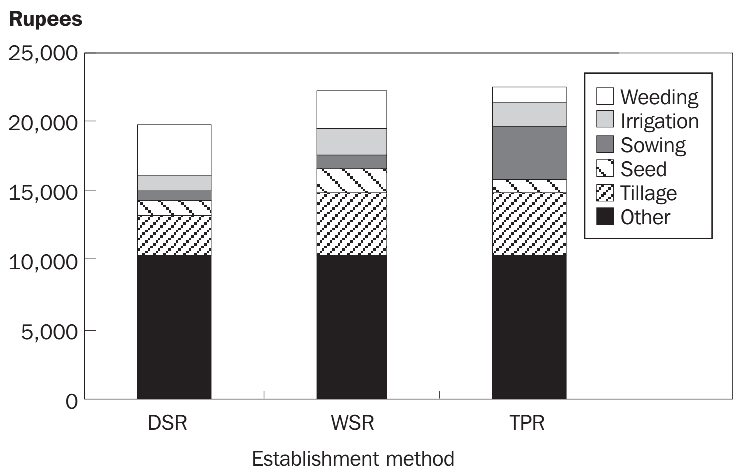

Fig. 1. Cost of rice establishment under three methods of crop establishment.

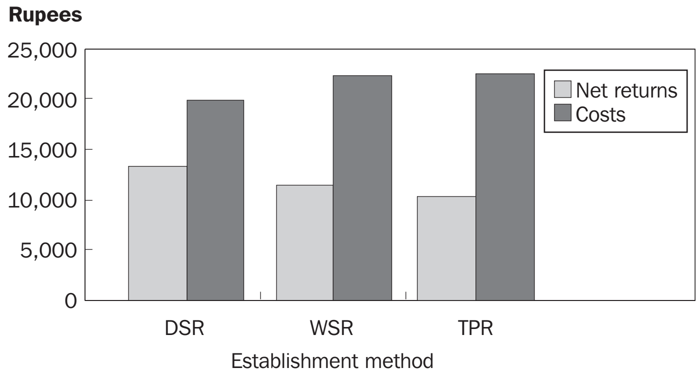

Fig. 2. Costs and net returns for rice under three methods of crop establishment.

Rice-wheat

Table 3 and Figure 4 show the profitability of the system as a whole. The cost of cultivation in direct-seeded rice was lower with both conventional tillage and zero-tillage than with other methods of rice establishment. Net returns in DSR were Rs. 45,000 ha^{-1} with conventional tillage against Rs. 40,120 ha^{-1} in wet-seeded rice and Rs. 36,435 ha^{-1} in transplanted rice. Net returns were still higher in zero-tillage at Rs. 47,612 ha^{-1} in dry-seeded rice, Rs. 45,292 ha^{-1} in wet-seeded rice, and Rs. 41,177 ha^{-1} in transplanted rice. Figures 2 to 4 clearly show that the overall profitability of the system depends on wheat. Net returns for wheat are twice the cultivation costs, whereas, for rice, net returns are always lower than production costs. Rice is therefore grown as a staple food crop for subsistence, whereas wheat is primarily a cash crop. The greater profitability of wheat highlights the potential benefits from DSR not only in reducing the cost of rice production but also in contributing to earlier planting of wheat by advancing the date of the rice harvest.

Labor use

Labor requirements in dry-seeded rice were substantially lower than in transplanted rice (Table 4). Labor use in dry-seeded rice was 139 labor days ha^{-1} in 2002 and 124 ha^{-1} in 2003, against 161.5 days and 156 days for transplanted rice. Labor use in dry-seeded rice and wet-seeded rice was not very different except for a few activities. The mean for two years shows that transplanted rice used 50 more days in land preparation and 7 more days in irrigation. However, dry-seeded rice used 30 more days in weeding. In total, transplanted rice required 27 more days than direct-seeded rice.

Cost-benefit analysis

Table 5 shows a sensitivity analysis based on costs and returns data from on-station trials at Pantnagar in the 2002 *kharif* season. Case A represents the base-scenario, whereas cases B, C, and D represent the scenarios for potential externalities, user costs, and labor displacement effects, respectively, of direct seeding with herbicides. Holding yields constant, the results show that

- Benefit-cost ratios for DSR and TPR would be equal if the environmental and health-related costs of direct seeding with herbicides were twice as high as private costs (Rs. 8,682 ha^{-1} versus Rs. 4,948 ha^{-1} for wet seeding and Rs. 8,585 ha^{-1} versus Rs. 3,851 ha^{-1} for dry seeding) (case B).

Table 2. Total cost of cultivation, gross income, and net returns of wheat establishment methods.[a]

Treatment	2002-03						2003-04					
	Gross income		Cost of cultivation		Net returns		Gross income		Cost of cultivation		Net returns	
	CTW	ZTW	CTW	ZTW	CTW	ZTW	CTW	ZTW	CTW	ZTW	CTW	ZTW
Dry-seeded rice	42,056	43,179	11,821	10,513	30,235	32,666	45,174	46,840	12,108	10,880	33,066	35,960
Wet-seeded rice	41,845	43,041	12,949	10,513	28,896	32,528	43,222	46,714	13,260	10,880	29,962	35,834
Transplanted rice	37,089	40,892	12,949	10,513	24,140	30,379	41,305	42,131	13,260	10,880	28,045	31,251

[a]All values are in Rs. ha^{-1}. CTW = conventionally tilled wheat, ZTW = zero-tillage wheat.
Source: Singh (2004).

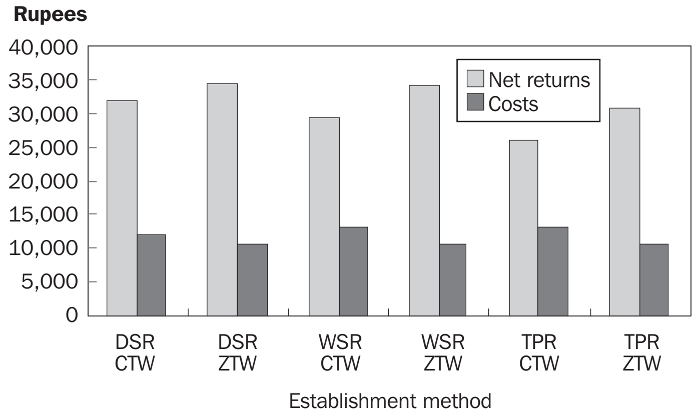

Fig. 3. Costs and net returns for wheat under three methods of rice crop establishment. Source: Table 2.

Table 3. Total cost of cultivation, gross returns, and net returns of rice-wheat establishment methods (mean of 2002 and 2003).[a]

Treatment	Cost of cultivation		Gross returns		Net returns	
	CTW	ZTW	CTW	ZTW	CTW	ZTW
Dry-seeded rice						
Rice	19,787	19,787	33,137	33,137	13,350	13,350
Wheat	11,965	10,677	43,615	45,009	31,650	34,332
Total	31,752	30,464	76,752	78,146	45,000	47,682
Wet-seeded rice						
Rice	22,257	22,257	33,849	33,849	11,592	11,592
Wheat	13,105	10,677	42,533	44,377	29,428	33,700
Total	35,362	32,934	76,382	78,226	41,020	45,292
Transplanted rice						
Rice	22,469	22,469	32,812	32,812	10,343	10,343
Wheat	13,105	10,677	39,197	41,515	26,092	30,834
Total	35,574	33,146	72,009	74,327	36,435	41,177

[a]All values are in Rs. ha^{-1}. CTW = conventionally tilled wheat, ZTW = zero-tillage wheat.
Source: Singh (2004).

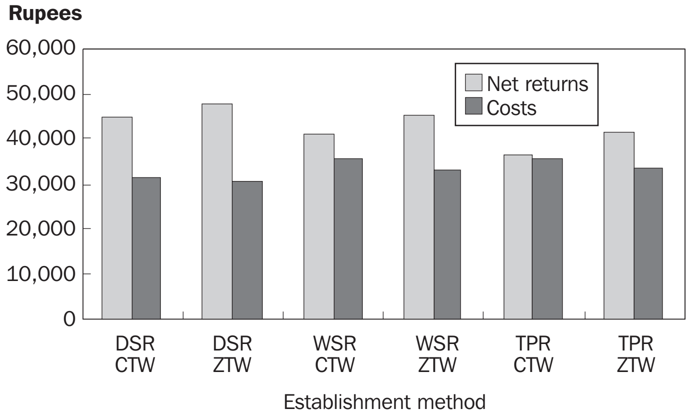

Fig. 4. Costs and returns for rice-wheat under three methods of rice crop establishment.

- Benefit-cost ratios for direct seeding would be equal to those of transplanting if rice yields fell by 40–50% (from 5.41 to 3.4 t ha^{-1} for wet seeding and 2.64 t ha^{-1} for dry seeding) (case C).
- Benefit-cost ratios for direct seeding would be equal to those of transplanting if the opportunity cost of labor were zero or negative (case D).

Discussion

Farmers have a financial incentive to adopt direct-seeded rice. Labor savings were 27 days ha^{-1} compared with those of transplanted rice. Total cost savings from DSR in the rice-wheat system came to Rs. 2,680 ha^{-1} over transplanted rice. This matches the experience with direct seeding elsewhere in Asia. In Malaysia, for example, farmers who direct-seeded used only 80 hours ha^{-1} per season compared with 237 hours ha^{-1} per season for transplanted rice, with a labor savings of 157 hours ha^{-1} per season. In total, the direct-seeded crop required only 34% of the labor required for the transplanted crop. With the adoption of direct seeding, farmers could rely substantially on their own family labor and their control over the timing of farming activities increased significantly (Wong and Morooka 1996).

Although based on on-station experiments, our results are supported by evidence from participatory evaluations of on-farm trials (Orr et al 2005). Evaluations were conducted in two villages in Faizabad District, eastern Uttar Pradesh, and in three villages in south Bihar. Most farmer participants had experience with DSR over two crop seasons. Saving labor was ranked as the most important advantage of DSR by farmers in Bihar, and the second most important benefit by farmers in eastern Uttar Pradesh. Saving tillage was ranked as the most important benefit of DSR in Uttar Pradesh. Saving water was ranked first and third in the two villages in Uttar Pradesh, and second, third, and fourth in the three villages in Bihar. Farmers saw the primary disadvantages of DSR as more weeds and consequently higher labor costs for weeding. The high cost of pendimethalin (Rs. 1,188 ha^{-1} in 2004) and the lack of a reliable supply chain for herbicides are also likely to be important disadvantages for poorer farmers.

Unlike Wong and Marooka (1996), we found no evidence of lower yields with direct-seeded rice. Farmer evaluations reported the same or equivalent yields (Orr et al 2005). Interestingly, the

Table 4. Labor use (in days per ha) in different rice establishment methods.

Treatments → Activity	Year 2002					Year 2003					Average of 2002 and 2003				
	DSR[a]	WSR	TPR	Difference of DSR over		DSR	WSR	TPR	Difference of DSR over		DSR	WSR	TPR	Difference of DSR over	
				WSR	TR				WSR	TR				WSR	TR
Land preparation	28.00	46.00	69.00	–18.00	–41.00	24.00	40.00	83.40	–16.00	–59.40	26.00	43.00	76.20	–17.0	–50.20
Irrigation	9.50	18.50	25.50	–9.00	–16.00	10.75	2.00	8.50	+8.75	+2.25	10.12	10.25	17.00	–0.13	–6.88
Weeding	45.76	26.00	11.00	+19.76	+34.76	33.30	18.56	8.00	+14.74	+25.30	39.53	22.28	9.50	+17.25	+30.03
Common costs	56.00	56.00	56.00	0	0	56.30	56.30	56.30	0	0	56.15	56.15	56.15	0	0
Total	139.26	146.5	161.50	–7.24	–22.24	124.35	116.86	156.20	+7.49	–31.85	131.80	131.68	158.85	+0.12	–27.05

[a]DSR = direct-seeded rice, WSR = wet-seeded rice, TPR = transplanted rice.
Source: Singh (2004).

Table 5. Sensitivity analysis of social profitability of direct seeding, Pantnagar, Uttaranchal (2002).

Case	Control method	Rice yield (t ha^{-1})[a]	Total variable cost (Rs. ha^{-1})[b] Labor	Total variable cost (Rs. ha^{-1})[b] Materials	Gross benefits (Rs. ha^{-1})[c]	Net benefits (Rs. ha^{-1})[d]	Benefit-cost ratio[e]
A							
	Transplanting	5.41	3,382	4,494	23,323	15,447	1.96
	Wet seeding	5.35	1,259	3,689	25,698	20,750	4.19
	Dry seeding	4.91	767	3,084	25,413	21,562	5.60
B	Allow material costs to change and hold yields constant						
	Transplanting	5.41	3,382	4,494	23,323	15,447	1.96
	Wet seeding	5.35	1,259	7,423	25,698	17,016	1.96
	Dry seeding	4.91	767	8,585	25,413	16,828	1.96
C	Allow yields to change and hold material costs constant						
	Transplanting	5.41	3,382	4,494	23,323	15,447	1.96
	Wet seeding	3.40	1,259	3,689	14,646	9698	1.96
	Dry seeding	2.64	767	3,084	11,399	7548	1.96
D	Allow cost of labor to change and hold yields constant						
	Transplanting	5.41	0	4,449	23,323	18,829	4.19
	Transplanting	5.41	–915	4,449	23,323	19,789	5.60
	Wet seeding	5.35	1,259	3,689	25,698	20,750	4.19
	Dry seeding	4.91	767	3,084	25,413	21,562	5.60

[a]Yields from on-station trials, G.B. Pant University, kharif season 2002, adjusted downward by 20% to allow for experimental conditions. [b]Variable costs of crop establishment and weed control only. Herbicides account for 58% of material costs for wet seeding and 43% for dry seeding, with the rest comprising payments for irrigation water and equipment hire. [c]Farm-gate price of Rs. 4.75 kg^{-1}. [d]Gross benefits minus total variable costs of crop establishment and weed control. [e]Net benefits divided by total variable costs of crop establishment and weed control.

wheat crop gave a higher grain yield after direct-seeded rice than after transplanted rice. Evidence from rice-wheat cropping systems shows that wheat yield depends on date of sowing. Adoption of direct seeding allows earlier rice harvesting and may increase wheat yields by allowing earlier sowing. However, farmer evaluations revealed that they valued DSR primarily because it reduced rice costs rather than because it allowed earlier sowing of wheat (Orr et al 2005).

Cost-benefit analysis suggests that DSR in eastern India is profitable. TPR is as socially profitable as DSR only when it is assumed that the opportunity cost of agricultural labor is zero, or rice yields are halved, or the social cost of herbicides on human health and the environment is twice the private costs. This seems unlikely. Take the opportunity cost of labor. Wage rates for peak-season activities are usually assumed to reflect opportunity costs (Gittinger 1982). In Uttar Pradesh, real wage rates for male agricultural labor have risen through a combination of labor militancy and opportunities for off-farm employment (Lerche 2002). The 1990s saw successful strikes for wage increases in peak periods (Srivastava 2002). However, transplanting is generally regarded as “women’s work” and work done by women is systematically undervalued. This makes the valuation of female labor problematic for any social cost-benefit analysis (Kabeer 1994).

Another approach is to use the compensation principle of welfare economics, which states that if those who gain from a change may compensate those who lose and still remain better off, then the change should be implemented. In this case, the farmers’ gain (Rs. 3,007 ha^{-1}) is much higher than the wage loss suffered by laborers (27 days × Rs. 60 day^{-1} = Rs. 1,620 ha^{-1}). Hence, farmers can compensate laborers and still remain better off. However, this principle is open to criticism on both logical and practical grounds. If it is possible for the gainers to compensate the losers, then the converse is also true, making it possible to use the compensation principle both to justify a change in policy and to justify a U-turn that reverses the same policy. The principle is also unrealistic because, in the real world, society does make value judgments about how income is distributed, and policies that leave poor people worse off are unlikely to be approved just because compensation can be paid *in principle* though not *in practice*.

Costs and benefits were analyzed in terms of economic efficiency. Equity has not been considered. Since DSR does not increase yields, it will not benefit labor by pushing down rice prices. Instead, it simply redistributes income from labor to farmers. Thus, DSR will reduce equity. Rice is transplanted mostly by women, who are less mobile than men and are therefore less able to find alternative employment. Locally, few alternative sources of employment may be available. For example, in Udham Singh Nagar District, Uttaranchal, farm labor is supplied by labor "colonies" that are physically and socially isolated and rely on a few large farmers for employment (Orr and Singh 2004). Lastly, wage income from transplanting is used to smooth consumption during slack periods when farm employment is not available. DSR would leave labor households more vulnerable to seasonal underemployment. Against this, DSR can benefit small farmers, including female family members (Orr et al, this volume).

The social cost of DSR may be reduced if labor is compensated by alternative employment. This might come through livelihood diversification into nonfarm employment, or if employers preferred to employ local rather than migrant labor, or if there was an increase in opportunities for employment in agriculture (e.g., weeding DSR) that favored local labor, especially women. In addition, under the changing socioeconomic environment in South Asia, young male workers may be unavailable or reluctant to undertake transplanting (Hobbs et al 2002).

Conclusions

Direct-seeded rice is technically feasible and economically viable, and may also help arrest the yield decline in the following wheat crop. These results are based on experimental conditions, however, and assume assured irrigation. Evidence from farmer evaluations confirmed that DSR reduced the costs of labor, tillage, and irrigation for rice. Farmers were less concerned about the benefits to the following wheat crop than the immediate cost savings for rice.

The potential impact of DSR on labor (especially women) raises important questions of equity. A social cost-benefit analysis is required to measure the implications of this new technology for social welfare. However, this will not change the fact that adoption of DSR cannot be prevented. As with other labor-saving technology, farmers will adopt DSR whenever they find it profitable to do so. This reinforces the importance of the growing nonfarm sector for sustainable rural livelihoods. It also illustrates the need for a broader social perspective in the strategies of researchers, planners, and policymakers.

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Notes

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Appendix 1. Treatment cost of rice production (Rs. ha^{-1}), 2002.

Operations	Dry-seeded rice[a]	Wet-seeded rice	Transplanted rice
	Cost	Cost	Cost
Land preparation			
Harrowing + planking	1,120	1,120	1,120
Bunding	1,122	1,122	1,122
Puddling (tractor)	–	1,660	1,660
Leveler	640	640	640
Seed drill sowing	640	–	–
Drum seeder sowing	–	1,020	–
Transplanting (uprooting + transplanting)[b]	–	–	786 + 1,668
Irrigation			
I (puddling)	–	776	792
II	576	672	680
III	536	656	672
IV	–	–	668
Weeding			
I	1,614	870	408
II	624	420	144
Herbicide application	508	283	120
Nursery			
Field preparation			
Harrowing	–	–	100
Bunding	–	–	60
Puddling (manually)	–	–	180
Weeding (2)	–	–	480
Irrigation (4)	–	–	320
Urea (90 kg N ha^{-1})	–	–	42
SSP (60 kg P ha^{-1})	–	–	56
$ZnSO_4$ (30 kg Zn ha^{-1})	–	–	76
Material cost			
Herbicide			
Pendimethalin (1 kg a.i. ha^{-1}) a.i. = 30%	1,336	–	–
Cyhalofopbutyl (1 L ha^{-1}) 10 EC	–	1,560	–
Butachlor (1.5 kg a.i. ha^{-1})	–	–	581
Seed rate (kg ha^{-1})	1,200	1,680	960
Total	9,916	12,479	13,235

[a]No presowing irrigation was done for DSR during sowing. [b]For 1 ha of transplanting of rice, a nursery area of 500 m^2 was required.

Appendix 2. Common cost of rice production (Rs. ha^{-1}), 2002.

Operations	Dry-seeded rice[a]	Wet-seeded rice	Transplanted rice
Fertilizer application	120	120	120
Insecticide/fungicide application	263	263	263
Harvesting (manually)	1,200	1,200	1,200
Threshing (manually)	1,800	1,800	1,800
Material cost			
Urea (120 kg N ha^{-1})	1,127	1,127	1,127
SSP (60 kg P ha^{-1})	1,125	1,125	1,125
MOP (40 kg K ha^{-1})	302	302	302
$ZnSO_4$ (30 kg Zn ha^{-1})	2,367	2,367	2,367
Insecticide			
Cartap hydrochloride (Veertap) (25 kg ha^{-1})	1,350	1,350	1,350
Fungicide			
Copper oxychloride (COC) (1 kg ha^{-1})	220	220	220
Streptocyclin (15 g ha^{-1})	723	723	723
Total	9,945	9,945	9,945

	Item	**Cost (Rs.)**		**Item**	**Cost (Rs.)**
1.	Tractor	200 h^{-1}	9.	Pendimethalin	400 L^{-1}
2.	Labor	60 day^{-1}	10.	Cyhalofopbutyl	1,560 L^{-1}
3.	Irrigation	40 h^{-1}	11.	Butachlor	160 L^{-1}
4.	Seed (rice)	24 kg^{-1}	12.	Cartap hydrochloride	54 kg^{-1}
5.	Urea	432 q^{-1}	13.	Copper oxychloride	220 kg^{-1}
6.	SSP	300 q^{-1}	14.	Streptocyclin	296 g^{-1}
7.	MOP	452 q^{-1}	15.	Rice	530 q^{-1}
8.	$ZnSO_4$	18.15 kg^{-1}	16.	Rice straw	520 kg^{-1}

Appendix 3. Treatment cost of rice production (Rs. ha^{-1}), 2003.

Operations	Dry-seeded rice[a]	Wet-seeded rice	Transplanted rice
Land preparation			
Harrowing + planking	1,060	1,060	1,060
Bunding	1,110	1,110	1,110
Puddling (tractor)	–	1,700	1,700
Leveler	600	600	600
Seed drill sowing	640	–	–
Drum seeder sowing	–	1,008	–
Transplanting (uprooting + transplanting)[b]	–	–	852 + 1,692
Irrigation			
I (puddling)	–	796	792
II	568	680	–
III	552	–	–
Weeding			
I	1,230	696	348
II	270	141	11
Herbicide application	498	277	120
Nursery			
Field preparation			
Harrowing	–	–	100
Bunding	–	–	60
Puddling (manually)	–	–	180
Weeding (2)	–	–	480
Irrigation (4)	–	–	300
Urea (90 kg N ha^{-1})	–	–	47
SSP (60 kg P ha^{-1})	–	–	57
$ZnSO_4$ (30 kg Zn ha^{-1})	–	–	58
Material cost			
Herbicide			
Pendimethalin (1 kg a.i. ha^{-1}) a.i. = 30%	1,202.4	–	–
Cyhalofop butyl (1 L ha^{-1}) 10 EC	–	1,560	
Butachlor (1.5 kg a.i. ha^{-1}) a.i. = 50%			450
Seed rate (kg ha^{-1})	1,200	1,680	960
Total	8,920	11,308	10,976

[a]No presowing irrigation was done for DSR during sowing. [b]For 1 ha of transplanting of rice, a nursery area of 500 m^2 was required.

Appendix 4. Common costs for different establishment methods (Rs. ha^{-1}), 2003.

Operations	Dry-seeded rice[a]	Wet-seeded rice	Transplanted rice
Fertilizer application	120	120	120
Insecticide/fungicide application	259	259	259
Harvesting (manually)	1,200	1,200	1,200
Threshing (manually)	1,800	1,800	1,800
Material cost			
Urea (120 kg N ha^{-1})	1,252	1,252	1,252
SSP (60 kg P ha^{-1})	1,141	1,141	1,141
MOP (40 kg K ha^{-1})	297	297	297
$ZnSO_4$ (30 kg Zn ha^{-1})	2,367	2,367	2,367
Insecticide			
Cartap hydrochloride (Veertap) (25 kg ha^{-1})	1,975	1,975	1,975
Fungicide			
Copper oxychloride (COC) (1 kg ha^{-1})	278	278	278
Streptocyclin (15 g ha^{-1})	95	95	95
Total	10,783	10,783	10,783

	Item	Cost (Rs.)		Item	Cost (Rs.)
1.	Tractor	200 h^{-1}	9.	Pendimethalin	360 L^{-1}
2.	Labor	60 day^{-1}	10.	Cyhalofopbutyl	1,560 L^{-1}
3.	Irrigation	40 h^{-1}	11.	Butachlor	150 L^{-1}
4.	Seed (rice)	24 kg^{-1}	12.	Cartap hydrochloride	79 kg^{-1}
5.	Urea	480 q^{-1}	13.	Copper oxychloride	278 kg^{-1}
6.	SSP	304 q^{-1}	14.	Streptocyclin	386 g^{-1}
7.	MOP	445 q^{-1}	15.	Rice	530 q^{-1}
8.	$ZnSO_4$	13.75 kg^{-1}	16.	Rice straw	520 kg^{-1}

Appendix 5. Treatment cost of wheat production (Rs. ha^{-1}), 2002-03.

Operations	CTW after DSR	CTW after WSR	ZTW after DSR, WSR, and TPR
Land preparation			
Harrowing + planking	1,120	1,380	–
Roller	–	200	–
Rotavator	–	680	–
Leveler	640	640	–
Seed drill sowing	600	600	640
Bunding	600	600	600
Irrigation	544	532	456
Material cost			
Seed	2,000	2,000	2,500
Total	5,504	6,632	4,196
Material cost			
Fertilizer			
Urea (120 kg N ha^{-1})	907	907	907
DAP (60 kg P ha^{-1})	1,092	1,092	1,092
Herbicide			
Metsulfuronmethyl (4 g a.i. ha^{-1})	350	350	350
Isoproturon (1 kg a.i. ha^{-1})	260	260	260
Operations			
Fertilizer application	120	120	120
Herbicide application	588	588	588
Harvesting (manually)	1,200	1,200	1,200
Threshing (manually)	1,800	1,800	1,800
Total	6,317	6,317	6,317

	Item	Cost (Rs.)
1.	Tractor	200 h^{-1}
2.	Labor	60 day^{-1}
3.	Irrigation	40 h^{-1}
4.	Seed (wheat)	20 kg^{-1}
5.	Urea	432 q^{-1}
6.	DAP	840 q^{-1}
7.	Metsulfuron methyl	1,408 g^{-1}
8.	Isoproturon	200 kg^{-1}
9.	Wheat	630 q^{-1}
10.	Wheat straw	180 q^{-1}

Appendix 6. Treatment cost of wheat production (Rs. ha^{-1}), 2003-04.

Operations	CTW after DSR	CTW after WSR	ZTW after DSR, WSR, and TPR
Land preparation			
Harrowing + planking	1,080	1,340	–
Roller	–	240	–
Rotavator	–	660	–
Leveller	600	600	–
Seed drill sowing	640	640	680
Bunding	624	624	624
Irrigation	528	520	440
Material cost			
Seed	2,000	2,000	2,500
Total	5,472	6,624	4,244
Material cost			
Fertilizer			
Urea (120 kg N ha^{-1})	1,008	1,008	1,008
DAP (60 kg P ha^{-1})	1,208	1,208	1,208
Herbicide			
Metsulfuronmethyl (4 g a.i. ha^{-1})	400	400	400
Isoproturon (1 kg a.i. ha^{-1})	289	289	289
Operations			
Fertilizer application	120	120	120
Herbicide application	612	612	612
Harvesting (manually)	1,200	1,200	1,200
Threshing (manually)	1,800	1,800	1,800
Total	6,636	6,636	6,636

	Items	Cost
1.	Tractor	200 h^{-1}
2.	Labor	60 day–$^{-1}$
3.	Irrigation	40 h^{-1}
4.	Seed (wheat)	20 kg^{-1}
5.	Urea DAP	480 q–$^{-1}$
6.	Metsulfuron methyl	926 q^{-1}
7.	Isoproturon	1,608 g^{-1}
8.	Wheat	200 kg^{-1}
9.	Wheat straw	630 q^{-1}
10.	Tractor	180 q^{-1}

Appendix 7. Cost of cultivation of wheat (Rs. ha^{-1}), 2002-03.

Treatment	Land preparation	Seed drill	First irrigation	Seed cost	Total treatment cost	Common cost of cultivation	Total cost
Dry-seeded rice							
Conventional-tillage wheat	2,360	600	544	2,000	5,504	6,317	11,821
Zero-tillage wheat	600	640	456	2,500	4,196	6,317	10,513
Wet-seeded rice							
Conventional-tillage wheat	3,500	600	532	2,000	6,632	6,317	12,949
Zero-tillage wheat	600	640	456	2,500	4,196	6,317	10,513
Transplanted rice							
Conventional-tillage wheat	3,500	600	532	2,000	6,632	6,317	12,949
Zero-tillage wheat	600	640	456	2,500	4,196	6,317	10,513

Appendix 8. Cost of cultivation of wheat (Rs. ha^{-1}), 2003-04.

Treatment	Land preparation	Seed drill	First irrigation	Seed cost	Total treatment cost	Common cost of cultivation	Total cost
Dry-seeded rice							
Conventional-tillage wheat	2,304	640	528	2,000	5,472	6,636	12,108
Zero-tillage wheat	624	680	440	2,500	4,244	6,636	10,880
Wet-seeded rice							
Conventional-tillage wheat	3,464	640	520	2,000	6,624	6,636	13,260
Zero-tillage wheat	624	680	440	2,500	4,244	6,636	10,880
Transplanted rice							
Conventional-tillage wheat	3,464	640	520	2,000	6,624	6,636	13,260
Zero-tillage wheat	624	680	440	2,500	4,244	6,636	10,880

Appendix 9. System-wide total cost of cultivation, gross income, net income, and benefit-cost ratio of rice-wheat system (in Rs. ha^{-1}).

Treatments	2002-03				2003-04			
	Total cost of cultivation	Gross income	Net income	Benefit-cost	Total cost ratio	Gross income of cultivation	Net income	Benefit-cost ratio
DSR-CTW	31,682	74,897	43,215	1.36	31,821	78,608	46,787	1.47
DSR-ZTW	30,374	76,020	45,646	1.50	30,593	80,274	49,681	1.62
WSR-CTW	35,373	73,585	38,212	1.08	35,351	79,179	43,828	1.24
WSR-ZTW	32,937	74,781	41,844	1.27	32,971	82,671	49,700	1.51
TPR-CTW	36,129	68,594	32,465	0.90	35,019	75,423	40,404	1.15
TPR-ZTW	33,693	72,397	38,704	1.15	32,639	76,249	43,610	1.34

Prospects for direct-seeded rice in eastern India: socioeconomic perspectives

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Prospects for the adoption of direct-seeded rice (DSR) in eastern India are brighter than previously thought. Evidence is drawn from an analysis of existing crop management practices for transplanted rice (TPR) in kharif 2003 and farmer evaluation of on-farm trials. Results showed no difference in average time of transplanting by farm size, which suggests that small as well as large farms will benefit from timelier crop establishment. Livelihood diversification through seasonal migration has increased incentives for the adoption of labor-saving technology, although this is reduced by the "feminization" of agriculture whereby female family members substitute for men. DSR will benefit poorer farmers by reducing the climatic risk and their dependence on hired pumpsets and tractors for timely crop establishment. Larger farmers may benefit primarily from savings in the costs of mechanized tillage and irrigation rather than savings in labor costs.

Prospects for the adoption of direct-seeded rice (DSR) are based largely on historical experience in Southeast Asia, where rapid urbanization and growth in rural nonfarm employment have encouraged farmers to adopt labor-saving technology. This has led to the conclusion that in India, "where population density is high and overall economic growth has been slow, economic incentives for a shift to direct seeding are likely to remain weak" (Pandey and Velasco 2002).

This paper argues that prospects for the adoption of DSR in eastern India may be brighter than previously thought, because

- Seasonal migration and urbanization have reduced rural labor supply,
- Labor savings will be shared by small as well as large farms,
- DSR can reduce production risk in rainfed rice, and
- Adoption may be driven by other factors besides labor costs.

The analysis is necessarily ex ante because DSR is not yet widely grown in India outside the upland rice environment. Consequently, the prospects for DSR adoption are explored through an analysis of existing crop management practices for transplanted rice (TPR) and through farmers' experience with DSR in on-farm trials (OFTs).

Analysis focuses on the farm household. Although DSR offers farmers significant cash savings, the distribution of potential benefits at the farm level has received little attention. At first sight, it might seem that benefits will go only to larger farmers who rely heavily on hired labor. However, small farmers may also hire labor at peak periods, particularly when they rely for income on off-farm employment. If so, they may also share (though not equally) in the benefits from labor-saving technology. Specifically, therefore, this paper examines three questions:

- Is timely transplanting and weeding related to farm size?
- If not, what factors determine timeliness?
- What are the likely drivers and constraints on DSR adoption?

The next section describes the sources of data and the methods used in the analysis. Results are presented and discussed in the following sections. The final section concludes.

Data and methods

Baseline surveys

The analysis is based on baseline surveys conducted during the 2003 kharif season (May-November) in eastern India. Unlike 2002, which saw a drought, or 2004, when rainfall was scanty, the survey year 2003 was one of "normal" rainfall at our research sites.

In Uttar Pradesh State, the survey was conducted in four villages (Sorawn, Sultanpur District, and Toromaphy, Kharbadiya, and Inayatnagar, Faizabad District). In Bihar State, the survey was made in three villages (Sardali Chak, Patna District; Dhangain, Rohtas District; and Korawan, Nalanda District). Villages were selected, purposively, as the sites of DSR OFTs. Irrigation was chiefly from tubewells except in Sorawn and Korawan, where water was also supplied by canals. Within each village, a random sample of farmers was selected stratified according to four farm size categories (<1, 1–2, 2–4, 4+ ha). Thirty farm households were sampled from each village. The final sample size was 117 in Uttar Pradesh and 99 in Bihar. Data were collected by trained enumerators in two rounds using a structured questionnaire (Orr 2005). Information on crop management practices was collected by plot, while information on labor use, assets, and sources of income was collected at the household level. The surveys were administered by Narendra Dev University of Agriculture and Technology, Faizabad, and Rajendra Dev University, Patna. For convenience, they are referred to here as the "Faizabad" and "Patna" surveys.

For tabular analysis, farms were grouped into terciles according to farm size (Table 1), date of transplanting (Tables 2 and 3), timeliness of first weeding (Tables 4 and 5), and the mean area planted to rice (Table 6). To derive mean dates of transplanting and weeding at the farm level, the date for individual plots was weighted by its share in the total area planted to rice. Statistically significant differences between terciles were determined using ANOVA (for numerical variables) and Chi-square (for categorical variables). Multivariate analysis (linear regression) was used to identify determinants of date of transplanting at the plot level.

Farmer perceptions

Farmer perceptions of DSR are based on two evaluations made by farmers who had participated in OFTs in the 2003 and 2004 kharif seasons. The first of these involved 19 farmers in Udham Singh Nagar District, Uttaranchal (Orr and Singh 2004). The second involved 10 farmers from Kharbadiya and Toromaphy villages in Faizabad District; and 20 farmers from three villages in south Bihar, namely, Madadpur, Patna District; Dhangain, Rohtas District; and Korawan, Nalanda District (Orr et al 2005). The farmers who participated in these evaluations were mostly larger, "progressive" farmers whose views on DSR may differ from those of small and marginal farmers. The first evaluation used a structured questionnaire to systematically compare farmers' perceptions of the advantages and disadvantages of DSR with those of researchers. The second used group interviews to identify farmers' own perceptions of advantages and disadvantages. Both evaluations included formal ranking of advantages and disadvantages of DSR and recording of verbal comments.

Table 1. Socioeconomic profile of sample farms, Faizabad and Patna (2003).

Variable	Small farms	Medium farms	Large farms	All farms	P[a]
Faizabad					
Sample size	39	39	39	117	
Farm size (ha)	0.2	0.4	0.9	0.5	0.000
Upper caste (no.)	2	5	15	22	0.000
Area planted to rice (ha)	0.2	0.4	0.9	0.5	0.000
Household income from agriculture (%)	40.8	45.4	59.6	49.0	0.000
Nonagriculture income (%)					
Business	11.6	6.6	7.8	8.7	0.407
Labor	32.8	22.9	6.5	20.3	0.000
Service	4.0	8.7	12.4	8.5	0.080
Remittances	0.0	0.0	1.2	0.4	0.163
Other	10.8	16.3	12.5	13.1	0.079
Farm income (%)					
Rice	34.7	30.9	33.4	33.0	0.306
Wheat	39.0	36.2	38.2	37.8	0.516
Households owning					
Tractor	0	0	8	8	0.000
Pumpset	9	18	36	63	0.000
Bullocks (no.)	0.9	1.0	1.2	1.0	0.225
Rice self-sufficiency (months)	6.8	8.2	10.8	8.6	0.000
Patna					
Sample size (no.)	33	33	33	99	
Farm size (ha)	0.7	2.0	3.6	2.1	0.000
Upper caste (no.)	2	5	5	12	0.426
Area planted to rice (ha)	0.7	1.7	3.1	1.8	0.000
Household income from agriculture (%)	81.2	88.6	84.9	84.8	0.311
Nonagriculture income (%)					
Business	11.2	11.2	8.6	10.3	0.761
Labor	5.0	0.0	0.7	1.9	0.007
Service	2.2	0.2	5.3	2.7	0.082
Remittances	0.1	0.0	0.0	0.0	0.360
Other	0.3	0.0	0.5	0.3	0.589
Farm income (%)					
Rice	53.8	51.8	54.1	53.2	0.826
Wheat	29.1	30.8	27.9	29.2	0.614
Households owning					
Tractor	2	2	10	14	0.005
Pumpset	20	26	29	75	0.031
Bullocks (no.)	0.1	0.0	0.2	0.1	0.325
Rice self-sufficiency (months)	11.7	12.0	12.0	11.9	0.016

[a]Probability of a significant difference between terciles by Chi-square test or ANOVA.
Source: Baseline surveys.

Table 2. Constraints on transplanting, by time of transplanting, Faizabad (2003 season).

Variable	Tercile 1 (N = 39)	Tercile 2 (N = 39)	Tercile 3 (N = 39)	All farms (N = 117)	P^a
Mean date of transplanting	5 July	14 July	5 Aug	15 July	0.000
Area planted to rice (ha)	0.52	0.57	0.39	0.49	0.104
Source of irrigation (ha)					
Own tubewell	0.27	0.43	0.20	0.30	0.028
Canal	0.11	0.02	0.02	0.05	0.063
Other	0.10	0.04	0.10	0.07	0.084
Family labor used for transplanting (no.)					
Adult males	1.56	2.08	1.85	1.83	0.185
Adult females	0.56	0.79	1.00	0.79	0.071
Households hiring-out family labor for transplanting (no.)	27	22	32	78	0.049
Households hiring-in labor for transplanting (no.)	34	32	34	100	0.759
Area transplanted by (ha)					
Family labor only	0.04	0.05	0.04	0.04	0.937
Hired labor only	0.13	0.14	0.02	0.10	0.113
Both hired and family labor	0.33	0.38	0.33	0.35	0.768
Area tilled by (ha)					
Tractor	0.17	0.12	0.09	0.13	0.423
Bullock	0.18	0.20	0.24	0.21	0.684
Both	0.09	0.17	0.02	0.09	0.034
Tillage (ha)					
Own tractor	0.08	0.04	0.05	0.06	0.749
Own bullock	0.15	0.18	0.21	0.18	0.692
Both	0.06	0.14	0.00	0.07	0.051
Upper caste households (no.)	9	7	6	22	0.676

[a]Probability of a significant difference between terciles by Chi-square test or ANOVA.
Source: Baseline survey.

Results

Socioeconomic profile

In Faizabad, larger farms had a higher share of income from agriculture, with a lower share of nonfarm income from labor and a higher share from "service" or salaried employment (Table 1). Large farms were also more self-sufficient in rice, and were more likely to own tractors and pumpsets than smaller farmers. The pattern was similar in Patna. Farmers in Patna had a higher share of household income from farming (85%) and from rice (53%), whereas household income in Faizabad was more diversified. In Patna though not in Faizabad, upper caste households were concentrated among large farms.

Timeliness of transplanting

In Faizabad, the mean transplanting date varied by 30 days (5 July-5 August) between the terciles (Table 2), whereas, in Patna, the range between terciles was only 14 days (15-29 July) (Table 3). Results showed that date of transplanting at the farm level was significantly related to

Table 3. Constraints on transplanting, by time of transplanting, Patna (2003 season).

Variable	Tercile 1 (N = 33)	Tercile 2 (N = 33)	Tercile 3 (N = 33)	All farms (N = 99)	*P*[a]
Mean date of transplanting	15 July	23 July	29 July	22 July	0.000
Area planted to rice (ha)	1.92	1.59	1.94	1.81	0.457
Type of irrigation (ha)					
None	0.19	0.13	0.16	0.16	0.724
Own tubewell	1.53	0.64	0.67	0.94	0.000
Canal	0.20	0.81	1.12	0.71	0.015
Family labor used for transplanting (no.)					
Adult males	3.45	2.97	2.39	2.94	0.001
Adult females	0.06	0.21	0.30	0.19	0.214
Households hiring-out family labor for transplanting (no.)	4	1	4	9	0.333
Households hiring-in labor for transplanting (no.)	22	28	31	81	0.014
Area transplanted with (ha)					
Family labor only	0.21	0.12	0.03	0.12	0.069
Hired labor only	0.33	0.78	1.11	0.74	0.061
Both hired and family labor	1.38	0.69	0.80	0.96	0.043
Area tilled by (ha)					
Tractor	1.82	1.48	1.75	1.69	0.541
Bullock	0.06	0.06	0.00	0.04	0.357
Both	0.03	0.05	0.19	0.09	0.370
Area tilled with own (ha)					
Tractor	0.74	0.33	0.39	0.49	0.380
Bullocks	0.06	0.06	0.00	0.04	0.398
Both	0.03	0.00	0.00	0.01	0.372
Upper caste households (no.)	1	3	8	12	0.025

[a]Probability of a significant difference between terciles by Chi-square test or ANOVA.
Source: Baseline survey.

- *Source of irrigation.* In both Faizabad and Patna, farms that transplanted early had greater access to irrigation through their own pumpsets and through canals.
- *Higher use of family labor*. In Patna, farms that transplanted earlier used more adult male family workers than others. This was not the case in Faizabad, however. An interesting contrast in the use of family labor for transplanting was the greater use of adult males in Patna (2.94 workers per household compared with 1.83) and the lower use of adult females (0.19 workers per household compared with 0.79).
- *Lower use of hired labor*. In Patna, farms that transplanted earlier relied more heavily on family labor working on its own or alongside hired workers and less heavily on hired labor working alone. Farms that transplanted earlier in Patna were also less likely to hire labor for transplanting.
- *Hiring-out family labor*. In both Patna and Faizabad, households that hired out family labor at the time of transplanting transplanted their own fields later than others.
- *Caste*. Upper caste households in Patna were less likely to transplant early, presumably because they avoided field labor or working alongside hired labor. However, this was not true of upper caste households in Faizabad.

Table 4. Constraints on weeding, by timeliness of first weeding, Faizabad (2003 season).

Variable	Tercile 1 (N = 39)	Tercile 2 (N = 39)	Tercile 3 (N = 39)	All farms (N = 117)	*P*[a]
Timeliness of first weeding (DAT)	22.9	25.8	32.6	27.1	0.000
Date of transplanting	19 July	14 July	11 July	15 July	0.000
Area planted to rice (ha)	0.41	0.45	0.62	0.50	0.031
Family labor used for first weeding					
Adult males	1.87	1.72	1.90	1.83	0.788
Adult females	0.87	0.77	0.72	0.79	0.709
Children	0.31	0.03	0.41	0.25	0.236
Households hiring labor for first weeding (no.)	29	34	29	92	0.280
Area weeded with (ha)					
Family labor only	0.07	0.04	0.06	0.06	0.577
Hired labor only	0.10	0.05	0.14	0.10	0.385
Both hired and family labor	0.24	0.36	0.37	0.32	0.244

[a]Probability of a significant difference between terciles by Chi-square test or ANOVA.
Source: Baseline survey.

Table 5. Constraints on weeding, by timeliness of first weeding, Patna (2003 season).

Variable	Tercile 1 (N = 33)	Tercile 2 (N = 33)	Tercile 3 (N = 33)	All farms (N = 99)	*P*[a]
Timeliness of first weeding (DAT)	24.7	29.4	34.7	29.6	0.000
Date of transplanting	26 July	22 July	19 July	22 July	0.000
Area planted to rice	1.73	1.85	1.85	1.83	0.907
Family labor used for first weeding (no.)					
Adult males	2.24	3.36	3.27	2.96	0.000
Adult females	0.33	0.12	0.06	0.17	0.093
Children	0.03	0.09	0.00	0.04	0.308
Households hiring labor for first weeding (no.)	11	18	17	46	0.174
Area weeded with (ha)					
Family labor only	0.16	0.05	0.18	0.13	0.187
Hired labor only	1.02	1.50	1.29	1.27	0.401
Both hired and family labor	0.56	0.31	0.38	0.42	0.565

[a]Probability of a significant difference between terciles by Chi-square test or ANOVA.
Source: Baseline survey.

Table 6. Variation in date of transplanting and first weeding, by area planted to rice (standard deviations).

Area planted to rice	Date of transplanting		Date of first weeding (DAT)	
	Patna	Faizabad	Patna	Faizabad
Tercile 1	7.1	8.6	3.6	5.5
Tercile 2	6.6	10.1	4.5	4.3
Tercile 3	11.1	9.9	4.8	8.7
Levene statistic for equality of variance	11.19	0.37	4.17	6.48
Probability	0.000	0.694	0.016	0.002

Table 7. Definitions of variables used in Table 8.

Variable	Definition
PCODE	Code for date of transplanting (1 = 10 June)
OWN	Dummy variable for land tenure (1 = owned, 0 = otherwise)
PUMPSET	Dummy variable if plot irrigated by own pumpset (1 = yes, 0 = otherwise)
TPFONLY	Dummy variable if plot transplanted using only family labor (1= yes, 0 = otherwise)
TPBOTH	Dummy variable if plot transplanted using both hired and family labor (1 = yes, 0 = otherwise)
OWNTRACT	Dummy variable if plot tilled using own tractor (1 = yes, 0 = otherwise)
LOW	Dummy variable for lowland (1 = yes, 0 = otherwise)
DURATION	Dummy variable for long-duration rice variety (1 = yes, 0 = otherwise)
VCODE	Dummy variable for Korawan village (1 = yes, 0 = otherwise)

In contrast, date of transplanting at the farm level was *not* significantly related to

- Farm size, or the area planted to rice.
- Use of tractors for tillage.
- Draft power ownership (either tractors or bullocks).

Timeliness of weeding

Differences in the timeliness of first weeding between farms were statistically significant, averaging 10 days between terciles (Tables 4 and 5). But constraints on weeding at the farm level differed between research sites:

- In Patna, timeliness was not significantly related to farm size, whereas, in Faizabad, weeding was less timely on larger farms.
- In Patna, though not in Faizabad, timely weeding was significantly related to use of family labor. Farms that weeded late used more family members for weeding than others.

Table 8. Regression estimates of timeliness of transplanting of kharif rice, Patna, 2003.

Variable	Date of transplanting (PCODE)		
	Standardized coefficients	T-value	Sig.
CONSTANT		35.606	0.000
OWN	–0.061	–1.334	0.183
PUMPSET	–0.177	–3.859	0.000
TPBOTH	0.059	1.142	0.254
TPFONLY	0.008	0.144	0.886
OWNTRACT	–0.196	–4.366	0.000
DURATION	–0.131	–2.935	0.004
LOW	0.095	2.186	0.029
VCODE	–0.462	–8.793	0.000
Adjusted R^2	0.313		
Sample size	373		

At both sites, no relationship was found between timeliness and whether or not farms hired labor for weeding. Similarly, timeliness was not related to the share of area planted to rice that was weeded with hired labor.

Variations in timeliness

Variation in timeliness between farms was compared by measuring the range of dates for transplanting and first weeding on each plot, with plots grouped into terciles according to farm size group. Size groups were defined according to the area planted to rice. The Levene test showed significant differences in the variance between terciles (Table 6). In Patna, larger farms had greater variation in date of transplanting and in timeliness of first weeding. In Faizabad, larger farms had greater variation in timeliness of first weeding but not in mean date of transplanting.

Determinants of timely transplanting

Multivariate analysis was used to determine the constraints on early transplanting for Patna farms. Average date of transplanting for each plot was specified to depend on eight independent variables (Table 7). We hypothesized that transplanting would be *earlier* on plots that were owned by the farmer, irrigated by his own pumpset, transplanted by family labor or a mix of family and hired labor, tilled by the farmer's own tractor, on lowland to avoid the risk of flooding, and on plots where farmers planted long-duration rice varieties. We also included a dummy variable for Korawan village, where farmers relied primarily on canal irrigation. The equation was estimated using OLS. Although the specification explained only 30% of the variation in transplanting date, five independent variables were statistically significant at the 10% level or better (Table 8). Results showed that transplanting was earlier on plots where

- Irrigation was provided by the farmer's own pumpset,
- Land was prepared by the farmer's own tractor,
- Farmers planted long-maturing varieties, and
- Farmers had access to canal irrigation (Korawan village).

Unexpectedly, transplanting date was significantly later on low-lying plots despite the risk of flooding. *The likely reason is that rainwater drains more quickly from highland, which is trans-*

Table 9. Farmer perceptions of advantages of direct seeding, U.S. Nagar District, Uttaranchal (2004).

Advantage	Response (no.)			Rank (max = 1)	Score (max = 20)
	True	False	Don't know		
Needs less time and energy for tillage	19	0	0	2.1	17.8
Reduced wear and tear on tractor	18	0	0	4.2	13.9
Less irrigation water needed before sowing (puddling)	16	3	0	2.8	15.5
Less labor needed for planting	19	0	0	2.6	17.8
Earlier planting of rice	10	9	0	7.1	12.6
Crop more tolerant of drought	15	3	1	7.2	11.9
Crop more responsive to fertilizer	12	4	3	7.0	12.6
Crop matures earlier	10	8	1	6.7	13.4
Crop harvested earlier	10	8	1	6.6	12.6
Rice yield is higher	5	12	2	4.0	15.3
Soil structure better for following crop	15	3	1	7.0	12.5
Following crop is planted earlier	19	0	0	4.7	15.4
More choice of following crop	8	11	0	6.2	11.0
Less tillage needed for following crop	9	9	1	7.9	12.8
Yield of following crop is higher	3	5	11	8.0	18.0
Other[a]	8	0	0	3.2	18.7

[a]Less irrigation needed after sowing (7 cases): no nursery needed, less pesticide needed (1 case).
Source: Orr and Singh (2004).

planted first. Date of transplanting was not significantly related to the type of labor used for transplanting or to land tenure.

Farmer perceptions

Farmers noted the following advantages of DSR:

- Most farmers agreed that DSR reduced the need for tillage, puddling, and labor required for transplanting (Table 9).
- Farmers saw the top three advantages of DSR as reduced time and energy for tillage (rank 2.1), reduced labor for planting (rank 2.6), and reduced need for irrigation after sowing (rank 3.2).
- There was less consensus on whether DSR allowed earlier maturity and harvest, or whether DSR allowed greater choice for the following crop. These advantages of DSR received relatively low rankings (ranks 6.7, 6.8, and 6.2, respectively).
- The majority of farmers (12 of 17) believed that yields were lower with DSR than with TPR. However, many reported that the difference was minimal.

Similarly, farmer-evaluators in Faizabad (eastern Uttar Pradesh) saw the most important advantage of DSR as savings in the cost of tillage because of the high cost of renting tractors. Only farmer evaluators in Bihar saw the primary advantage of DSR as savings in labor costs (Orr et al 2005).

Verbal comments from farmer-evaluators revealed the complex choices that farmers faced in adopting DSR, balancing the need to optimize expenditure on tillage and irrigation in relation to the timing of monsoon rainfall (Box 1).

Discussion

Diversification

Though lower than in Southeast Asia, in the past three decades India's rate of economic growth has improved remarkably. From 1972 to 1982, GDP growth averaged 3.5% a year—the so-called "Hindu rate of growth." But, in the 1990s, average annual growth in gross domestic product (GDP) per head reached 6%. If this rate is maintained, GDP per person will double in only 18 years. Furthermore, the benefits of economic growth have been widely distributed through migration. Seasonal migration is no longer simply a survival mechanism but a strategy for raising real income and acquiring assets (Deshingkar and Start 2003). Migrants include small and marginal farmers as well as landless laborers, suggesting that migration has become an important way to maintain the viability of small family farms (Rogaly and Coppard 2003, de Haan 2002).

Livelihood diversification was evident in Faizabad, where farming accounted for less than half of household income. After agriculture, "labor" provided the main source of household income. Much of this income came from out-migration. A recent study of three districts in eastern Uttar Pradesh revealed a high rate of out-migration (45%) among *farm* households (Paris et al 2005). This included both seasonal and long-term migration. Migration has improved the bargaining power of local labor by not only removing men from the labor force but by increasing the wage for which they are prepared to work. Higher "reservation wages" have forced farmers in Uttar Pradesh to raise wages for peak-period activities even when there is no physical shortage of labor (Srivastava 1997).

On the other hand, migration has increased women's workload within the household. Women and children in Faizabad were more likely to transplant and weed rice than in Patna (Tables 2 and 3). This may reflect weaker caste restrictions in Faizabad on female participation in field labor. But previous research in the same study area showed that women's participation in agriculture was higher in villages near cities where men could find employment. Women in lower caste households already contributed as much or more labor to rice cultivation than men, including most of the hired labor for transplanting and weeding (Paris et al 2000). Hence, livelihood diversification through seasonal migration or urban employment has encouraged the "feminization" of Indian agriculture (Kapadia and Lerche 1997).

Livelihood diversification has important implications for DSR adoption. By reducing the availability of male family labor on small farms, diversification should spur the adoption of labor-saving technology. But this incentive is blunted if women replace men in agriculture. A decisive factor for DSR adoption in Malaysia was the withdrawal of *female* labor from agriculture (Wong and Morooka 1996). In India, women's participation in agriculture is limited by ideologies of caste and gender (Rogaly 1997). This may encourage DSR adoption among households where men find off-farm employment. Making information about DSR available to women as well as to men would allow households to make better decisions about the allocation of family labor. Evidence suggests that including women in extending knowledge about new rice technology benefits the whole household (Paris et al 2005).

Box 1. Farmers' comments on DSR, Udham Singh Nagar District, Uttaranchal.

"Our utmost priority is to minimize costs of production. Some 200 liters of diesel now costs Rs. 6,000. So, first and foremost, we want to save on diesel." (Surmat Sood)

"TPR you can't leave dry for more than 1–2 days. With DSR, you can leave it dry for 8–10 days." (G.K. Sharma)

"Early irrigation is needed for DSR, yet temperatures are very high and maintaining moisture in the soil is difficult and costly. Yields may be lower because moisture regulation is difficult, especially at sowing. If the electricity fails, it's difficult because diesel is costly. You need 1.25 liters per hour, which costs Rs. 50. And it takes 8–10 hours to irrigate 0.4 ha of sandy soil. There's no moisture problem once the monsoon comes." (Ramesh Janeja)

"I plant nurseries as normal each year. If the rains are good, 20-30 June is the normal time for transplanting to get maturity in October. But, if there are good rains in early June or late May, then I do as much direct-sowing as possible. If the rain stops, I then go on to TPR. After early rains, there are hot winds that dry up the soil and the herbicide won't work. So, I sow the DSR in blocks of about 1.6 ha, and complete sowing and herbicide application for each block at a time. DSR can stand having no rain for a month or even more after sowing but the herbicide needs moisture or it's not effective." (D.S. Brar)

"It's recommended to sow before 10 June. This is peak summer. The big problem is with preirrigation. You need a big irrigation facility. We have tubewells. But, in April/May, the water table is very low and discharge is not good. It re-charges in July. Pendimethalin is very effective when you have soil moisture, but these are hot months and the water evaporates. You need a constant irrigation cycle. You need to irrigate every third day to make sure the pendimethalin will be effective, and the crop also needs irrigation every 3–4 days for 3 weeks before the rains set in. So, you have a dilemma—use the irrigation water to keep sowing more DSR, or use it to keep the rice already seeded in good condition and ensure the herbicide will be effective." (Surmat Sood)

"I haven't expanded the area under DSR because of the weed problem—herbicide doesn't control all the weeds, especially motha (Cyperus rotundus). *This is the main problem." (Amrit Pal Singh)*

"I buy pendimethalin from the shop with the best reputation and don't take the cheapest option. I check the expiry date." (Purshender Singh)

Source: Orr and Singh (2004).

Timeliness and labor use

Since average time of transplanting did not differ by farm size, transplanting on large farms was obviously not delayed by a shortage of labor. This suggests that an efficient labor market worked where large farms were not penalized by greater dependence on hired labor.

However, late transplanting in Patna was more common on farms that relied purely on hired labor, and where family labor did not work on its own or alongside hired labor. In this sense, hired labor was a constraint on timely transplanting. But this was not related to farm size. Instead, it reflected lower availability of family labor, with fewer adult males available for transplanting. This may reflect a caste ideology of work that forbids manual labor even in owned fields and which resulted in a supervision constraint on hired labor. Without the participation of family members, hired labor works more slowly and this might have delayed transplanting. Employers can overcome this constraint by substituting piece-rates for time-rates (daily wages), which have become increasingly common in regions of intensive rice farming (Kapadia 1996). Discussions with farmers, however, revealed that time-rates were still the most common method of payment for transplanting in the survey villages.

Weeding presented a slightly different picture. Although timeliness varied between farms, in Patna this was not related to farm size. Neither was it related to the use of hired labor, because there was no difference in the timeliness of weeding and the share of area that was weeded by hired labor. In Faizabad, however, first weeding was less timely on large farms.

The reasons for the absence of a labor constraint on large farms need further investigation. Migrant labor was uncommon, suggesting that the supply of local labor was adequate. Since most hired labor used for weeding is female, a gendered ideology of work that restricts women to working in their home village may result in a closed labor market. Women laborers worked outside the village only as members of a labor gang under a male contractor. Labor immobility ensured a ready supply of low-paid female labor on large farms.

In Patna, two important determinants of early transplanting were ownership of a tractor and of a pumpset. Tractor ownership allowed farmers to prepare land more quickly. Farmers who relied on bullocks or rented tractors for tillage were at a disadvantage. This constraint could be reduced either by increasing the supply of tractors for hire or by reducing the demand for tillage through the introduction of DSR. Adoption of DSR would therefore benefit farms in Patna that relied for tillage on animal draft power or rented tractors.

Ownership of a pumpset favors timely transplanting in several ways. “Average” rainfall occurs only one year in three (Sastri and Singh 2000). Irrigation allows farmers to prepare seedbeds early rather than waiting for monsoon rains. In drought years, transplanting may be impossible without irrigation, forcing farmers without irrigation to use wet or dry seeding (Pandey et al 2000). Irrigation also reduces the risk of yield loss from late-season drought. Previous research in Faizabad has shown that farmers with irrigation planted a higher share of cultivated area to rice and were more likely to grow modern varieties (Pandey et al 2000). Similarly, irrigation may reduce the downside risk from early transplanting. Farmers who transplanted early risked yield loss from a dry spell after the first rains. Those with their own pumpsets who did not have to rely on others for irrigation were more likely to take the risk of early transplanting.

Although ownership of tractors and pumpsets was concentrated among large farms, this did not translate into earlier transplanting at the farm level. This was because the larger number of plots meant that large farms had a greater range of transplanting dates (Table 6), and also because plots were physically scattered and often could not be irrigated from a single pumpset.

Risk

In Southeast Asia, DSR has been most widely adopted in the irrigated rice environment where the risk of crop failure is low. Thus, the benefits from DSR have been seen primarily in terms of reduced costs. In eastern India, however, rice is predominantly rainfed. Socioeconomic research on rice in this region has focused on the importance of risk in farmer decision-making for crop management and adoption of new technology (Singh et al 1995, 2000). Hence, the potential benefits from DSR include both lower costs and reduced risk.

Farmers' crop management practices with TPR suggest that DSR has the potential to reduce the risk of late transplanting in several ways:

- Reduced risk of erratic monsoon rainfall, since DSR requires less water for puddling and less irrigation after crop establishment.
- Reduced risk of market failure in the timely provision of draft power, irrigation, and labor.
- Reduced cost of buying water to establish a rice nursery to allow timely transplanting after the arrival of monsoon rains.

Adoption of DSR will therefore benefit smaller farmers who depend on the market for draft power and irrigation. However, DSR may also introduce new risks. For example, if presowing irrigation is needed to establish DSR and use herbicide effectively, farmers without their own pumpsets will still have to trust the market for the timely supply of irrigation water.

Adoption drivers and constraints

Surprisingly, farmers in Uttaranchal saw the main advantage of DSR as reducing tillage rather than reducing labor. Recent price hikes, which raised the price of diesel from Rs. 20–22 per liter in 2002 to Rs. 28 per liter in 2004, have increased the incentive for tractor owners to economize on fuel and expensive servicing. This suggests that DSR adoption in India may not necessarily follow the historical pattern in Southeast Asia. North India contains many large, mechanized farms that are run as a business by joint families with diverse sources of income (Jeffery 1997). With market liberalization, these farmers face spiraling costs for tillage and irrigation in the rice-wheat system. Incentives for DSR adoption may therefore vary regionally. Where the agrarian structure is characterized by many small farms, as in Bihar, DSR adoption may be driven by the need to economize on family labor and reduce risks. But, in regions with a similar agrarian structure, such as the Punjab, the cost of mechanized tillage and irrigation may emerge as the primary drivers of DSR adoption.

Although nearly all farmers interviewed were positive about DSR, only one had adopted it completely. The main constraint on expanding area under DSR was the problem of the "window" between seeding and the onset of the main monsoon rains (Box 1). The size of this window cannot be predicted in advance and might last several weeks. If farmers direct-seeded before the onset of premonsoon rains, they had to irrigate to ensure sufficient moisture for sowing and effective uptake of preemergence herbicides. Some farmers were prepared to take this risk and bear the cost of irrigation. Others opted for an "opportunist" strategy and direct-seeded only after the first premonsoon rains, otherwise they continued to transplant. Still others found the risks too high, especially where soils were sandy and the electricity supply was unreliable. Relying on diesel fuel for irrigation when the electricity supply failed was expensive, because the water table has declined over time and was lowest in April/May when rice was direct-seeded. These perceptions by farmers in Uttaranchal support the earlier findings from the baseline surveys in Faizabad and Patna on the importance of irrigation as an ex ante risk reduction strategy for early transplanting.

Conclusions

DSR is usually seen as part of the solution to the "yield problem" in the rice-wheat system. A livelihoods perspective helps to see the prospects for adoption of this new technology in a broader perspective.

Incentives for DSR adoption in India are seen as more limited than in Southeast Asia because of a slower rise in labor costs. However, this study in eastern India suggests that some mitigating factors may favor adoption.

- No difference was found in time of transplanting between small, medium, and large farms. Similarly, timely weeding was not related to farm size in Patna, though this was not the case in Faizabad. This suggests that the benefits from the adoption of DSR will not be confined solely to larger farms that rely chiefly on hired labor. Small farms may also share the benefits from labor-saving technology.
- Economic growth has accelerated with market liberalization, with the benefits from growth widely distributed through migration. In Faizabad, the popularity of seasonal migration as a livelihood strategy has reduced the availability of male labor in agriculture as well as pushed up the reservation wage at which men are prepared to work as agricultural labor.
- Livelihood diversification for men has increased the workload of women in agriculture, especially by women family members on small farms. DSR would reduce this workload and might allow women to move into higher-paying on-farm or even off-farm employment. Giving information about DSR directly to women would speed up this process.
- A farmer evaluation in Uttaranchal showed that larger farmers saw DSR as a way of reducing the costs of tractors and irrigation. Reducing labor costs was secondary. This suggests that, in parts of India where agriculture is dominated by large capitalist farms, adoption of DSR may not be driven exclusively by labor costs.
- In eastern India where rice is mostly rainfed, DSR can reduce climatic risk. Wealthier farmers reduce climatic risks for TPR by buying pumpsets and tractors. DSR may benefit poorer farmers by reducing the risk of market failure in obtaining irrigation water and tillage on time as well as by reducing the cost of buying these services. However, DSR will also introduce new risks, such as the need for presowing irrigation. In the final analysis, adoption of new technology in the rainfed rice ecosystem may be driven as much by the need to reduce risks as as to reduce costs.

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Dissemination and information flow processes in acceleration of zero-tillage technology: a case study

C.M. Singh and R.V. Pandey

An intensive study was conducted under the CABI project "Assessing impact for reaping the benefits of resource conservation technology" in two villages (Vishunpurva and Dammarjot) of Basti District in the northeastern Plain Zone (NEPZ) of Uttar Pradesh (India) during 2003-04. The data were collected by applying participatory rural appraisal tools from different socioeconomic categories of farm families, namely, large, subsistence, and marginal. The findings indicated that farmers' participatory on-farm demonstrations, exposure visit-cum-traveling seminars, and farmer-to-farmer (adopter to nonadopter) interaction were found to be the most effective and credible ways to develop confidence in the adoption of zero-tillage technology for sowing wheat in the rice-wheat cropping sequence. Large and then subsistence farmers adopted the technology in the early stage of dissemination, but marginal farmers did not because of limited capacity to bear risk coupled with a lack of technical know-how and resources. Extension scientists played a key role in technology delivery systems. In the study area, NDUAT, Kumarganj, Faizabad, through its Farm Science Center popularly known as Krishi Vigyan Kendra (KVK) and Farm Advisory Center known as Krishi Gyan Kendra (KGK) were the main source of effective information about zero-tillage technology in the rice-wheat system of eastern Uttar Pradesh.

An understanding of the processes of adoption of new technologies by a farming community has long been recognized as important for the programs of planning and implementation of research and transfer of technology. Farm household factors such as age, education, farm size, location, resources, technical knowledge, and competency have been underlined as the main factors affecting the adoption rate of an innovative technology.

In the process of technology dissemination, the conventional top-down extension system, which is based on the central source model of technology generation and diffusion, determines the role of various organizational arrangements and communication techniques in persuading farmers to adopt a recommended technology. It does not have much relevance with the felt need of farmers and their prevailing farming situations. Therefore, in technology transfer, the concept of extension has changed, focusing more on community-based participatory approaches such as the use of participatory rural appraisal (PRA) tools, farmers' participatory training and research (FPTR), or, more generally, participatory learning action (PLA) (Chambers 1997).

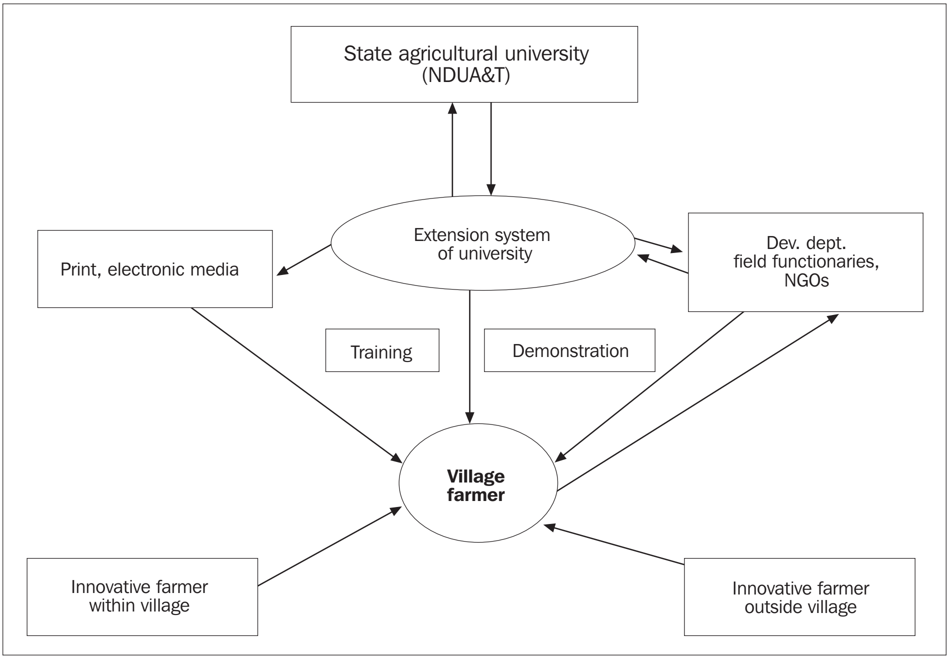

Fig. 1. Diagrammatic representation of the existing information flow.

Zero-tillage (ZT) technology (sowing of wheat after rice without field preparation) was first introduced for seeding of wheat in the rice-wheat system of the Indo-Gangetic Plains of eastern Uttar Pradesh in 2001-02, but could not diffuse in the farming community on a large scale (Singh et al 2003). The constraints to adopting zero-tillage were the nonavailability of drills, lack of knowledge, and lack of on-site training. The present system of information flow in the state lacks stakeholder participation, testing under farmer resource management, modern information and knowledge management tools, and logistic support. A systematic representation of the existing information flow in the field of agriculture is given in Figure 1.

The major concerns for dissemination of innovative technology such as ZT are shrinking the research and adoption gap, a widespread and sustainable use of the technology, profitability, equity, and low risk in a complex environment.

Barely 40% of the area planted to wheat is sown on time in the eastern part of the state. Most of the area is sown in December, followed by a limited area in the first week of January, resulting in poor yield. Information from farmers clearly reveals that the time available for a wheat seed-bed between the rice harvest and timely sowing of wheat is only 15–20 days. The conventional broadcasting method of wheat sowing varies from 3 to 6 plowings/harrowings and further delays in sowing result in loss of yield. Therefore, this time gap needs to be shortened by adopting ZT to reap the advantage of early crop establishment.

Table 1. Households in two study villages, by farm size.

Category	Vishunpurva		Dammarjot	
	No.	%	No.	%
Large	6	9	4	4
Subsistence	15	23	14	13
Marginal	33	50	81	76
Landless	12	18	7	7
Total	66	100	106	100

Methodology

Two villages, Vishunpurva (earlier adopted by Krishi Vigyan Kendra, Basti, for acceleration of ZT in a farmers' participatory mode) and Dammarjot (not adopted earlier), located in Basti District of eastern Uttar Pradesh, were selected for assessing the impact of conservation tillage during 2003 and 2004. Both villages contain a wide spectrum of farm families and are representative of the agroecological conditions in the eastern part of the state (Table 1).

To assess the impact of knowledge flow among the communities in both project villages, informal interviews were conducted with key informants using PRA techniques. Accordingly, farm families were categorized as large, subsistence, marginal, and landless on the basis of existing resources and landholdings. A livelihood impact assessment (LIA) was conducted by a multidisciplinary team of scientists using randomly selected respondents from each farmer category and users and nonusers of ZT. Informal focus groups, field visits, and farmer-scientist interaction (FSI) and meetings with development officials were used and awareness of the technology was measured by the increase in the area coverage. Experienced farmers were used to cross-check relevant questions.

Results and discussion

The reason for not using a machine (zero-till drill) in the nonadopter village (Dammarjot) indicates that all socioeconomic categories of farmers had never heard about ZT technology. Most had never even seen a single plot sown by a ZT drill in their life (CABI project report 2004). This reflects a conspicuous lack of promotional awareness that requires greater efforts by extension service personnel to provide creative avenues for innovation among farmers (Cummins 2003). The reasons for not using ZT technology are

- Neither seen nor heard about ZT.
- Not believable. Mind-set in favor of plowing.
- ZT drill not available in village.
- No demonstration by any department.
- No awareness training on ZT technology.

The current vision of technology dissemination is that of an agricultural university operating through its cooperating centers such as Krishi Vigyan Kendras (KVKs) and Krishi Gyan Kendras (KGKs) and following numerous types of information flow, including training, demonstration, field days, farmers' fair, farmer-scientist interaction, and farmer-to-farmer interaction, while the state department of agriculture is responsible only for creating awareness about subsidies for the purchase of ZT drills. The Rice-Wheat Consortium, based in New Delhi, gave financial support

Table 2. Agricultural knowledge flow systems identified.

Sources of knowledge/information	Vehicles of information
1. Government	Training
1.1 Agricultural University/KVK/KGK	Demonstration
	Field day
	Farmers' fair
	Farmer-scientist interaction
	Farmer-farmer interaction
	Literature
	Help-line
	Kisan call center
	Subsidy awareness
1.2 Department of Agriculture	Sale promotion
1.3 U.P. State Agro-Industrial Corporation	Radio talk
1.4 Electronic media	TV talk
2. Nongovernment	
2.1 Rice-Wheat Consortium	Exposure visit
3. Private sector	
3.1 Drill manufacturers	Exhibition
3.2 Print media	Newspapers
4. Others	
4.1 Neighbors	Chaupal meeting
4.2 Family members	Male head of household intervention

to the university to increase awareness of ZT technology through exposure visits-cum-traveling seminars. Neighbors played a key role in technology dissemination through Chaupal meetings (Table 2).

Farmers ranked different sources of information according to effectiveness (Table 3). The ranking was recorded on the basis of group interviews conducted during a PRA after a year of adoption. In terms of contact frequency, technical competency, and extent of adoption, the agricultural university extension system ranked first, followed by neighbors and male heads of household. Farmers ranked the Uttar Pradesh State Agro-Industrial Corporation and drill manufactures that supply the machine as the least effective.

The impact study showed that NDUA&T was the premier institution in launching the ZT program for seeding of wheat. Within three years (2001-02 to 2003-04), ZT covered 11,490 ha in 23 districts of eastern Uttar Pradesh (Table 4).

Figure 2 shows the new processes of dissemination and information flow used to accelerate the adoption of ZT technology. The active involvement of technology transfer centers such as KVKs and KGKs using participatory methods to work with farmers on-farm proved highly effective in disseminating ZT technology. Thus, participatory demonstrations, skill-oriented training, farmer-scientist interaction, farmer-to-farmer interaction, and exposure visits-cum-traveling seminars have been recognized as drivers of success. The overall economic gains from savings in field preparation, timely crop establishment, reduction in intensity of *Phalaris minor*, and reduced need for irrigation were the major incentives for adoption of the technology.

Table 3. Prioritization of effective sources for information flow in the adopter village (Vishunpurva).

Sources of knowledge	Contact frequency	Technical competency	Adoption extent	Rank
1. Government				
1.1 Agricultural University/KVKs & KGKs	***	***	***	I
1.2 Department of Agriculture	*	**	Nil	VII
1.3 U.P. State Agro-Industrial Corporation	Nil	**	*	VIII
1.4 Electronic media	**	**	***	IV
2. Nongovernment				
2.1 Rice-Wheat Consortium	*	**	*	VI
3. Private sector				
3.1 Drill manufacturers	Nil	*	Nil	IX
3.2 Print media	*	**	*	V
4. Others				
4.1 Neighbors	***	**	***	II
4.2 Family members	***	*	***	III

* = minor source, ** = intermediate, *** = major source.

Table 4. Horizontal shift in ZT coverage in eastern Uttar Pradesh.

Parameter	2001-02	2002-03	2003-04
Districts covered	17	20	23
Blocks covered	50	87	148
Villages covered	162	312	666
No. of farmers	290	835	3,822
Area sown under ZT (ha)	550	1,430	9,510
No. of ZT machines used	20	50	214

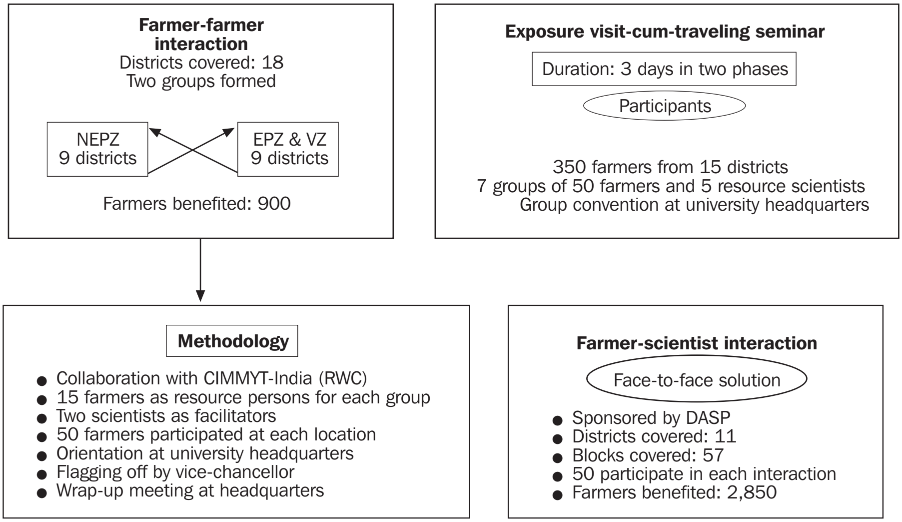

Fig. 2. Diagrammatic representation of new information flow.

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