Direct Seeding: Research Strategies and Opportunities

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IRRI

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Foreword

Asian rice systems are undergoing various types of change in response to economic factors and technological opportunities in farming. One such change has been a shift from transplanting to direct-seeding methods for rice establishment. While the rising cost of labor has provided economic incentives for direct seeding, the availability of short-duration rice varieties and chemical weed control methods has made such a shift economically profitable. Direct-seeding methods have also played a critical role in the intensification of Asian rice systems. In the future, in addition to the rising cost of labor, rice farmers of Asia will have to deal with an anticipated increasing scarcity of irrigation water as the demand for water from the urban and industrial sectors expands. Direct-seeding methods, especially dry seeding, may help in achieving higher water-use efficiency.

Despite the underlying trend toward direct seeding, the relative importance of direct seeding and transplanting varies among regions and ecosystems. Traditional direct-seeding systems with low productivity dominate in some areas, whereas successful transformations to high-productivity systems have occurred in others. Transplanting culture may also continue to dominate under certain environmental and socioeconomic conditions.

IRRI, together with the Rice Research Institute, Thailand, organized an international workshop on Direct Seeding in Asian Rice Systems: Strategic Issues and Opportunities, held on 25-28 January 2000 in Bangkok, Thailand. The objectives of this workshop were to review past patterns of changes in crop establishment and factors explaining such patterns, assess the likely future patterns of change in crop establishment in various ecosystems and regions, and identify strategic research issues for improving rice productivity by manipulating crop establishment methods and related factors. IRRI and national agricultural research and extension system partners are already making considerable efforts to develop more productive and sustainable direct-seeding systems. Although two previous workshops sponsored by IRRI (in 1990 and 1995) focused on the wet-seeding method, this workshop emphasized dry seeding. A cross-ecosystems perspective was taken so that the output of the workshop would be relevant to all rice production environments. The workshop helped identify strategic research issues on crop establishment methods covering aspects such as land preparation; weed, water, and crop management; and crop improvement.

This publication contains the papers presented at the workshop and the major research issues identified during the group discussions. We hope that this will be a useful source of information as we move forward in this important theme of research.

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Director General

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The needs for and challenges of direct seeding

Economics of direct seeding in Asia: patterns of adoption and research priorities

S. Pandey and L. Velasco

Direct seeding for rice establishment is spreading rapidly in Asia. This paper provides an overview of the patterns of adoption of direct-seeding methods in Asia. The rising wage rate, increasing availability of chemical weed control methods, and the need to intensify rice production systems were considered to be the major driving forces. The potential advantages and problems with direct seeding are discussed and the likely future patterns of changes are indicated. Finally, research priorities for improving the productivity of direct-seeding systems are presented.

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. 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 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. This paper provides a brief overview of the patterns of changes in crop establishment methods that have taken place in Asia and their impact and implications for research and technology development.

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

Dry seeding is probably the oldest method of crop establishment. Historical accounts of rice cultivation in Asia indicate that, during its early period of domestication, rice used to be dry sown in a mixture with other crops that were established under the shifting cultivation system (Grigg 1974). This extensive system of land use gave way to more intensive rice systems, especially in river valleys, as the population pressure on land increased with population growth. Transplanting, weeding, fertilization, and elaborate water management systems evolved over time. The increased labor supply resulting from population growth made the use of labor-intensive methods of rice production possible. By the 1950s, transplanting had become the dominant method of crop establishment in most of Asia. Dry seeding was practiced only in those areas where low population density and/or severe climatic/hydrological constraints prevented intensification of rice systems.

Accurate data on the proportion of rice area established by different methods are scanty. Published agricultural statistics in most countries do not include such data. As a result, information on this has to be culled from several data sources. Table 1 presents rough estimates for major rice-growing areas. The direct-seeded area in Asia is about 29 million ha, which is approximately 21% of the total rice area in the region. This estimate also includes upland and submergence-prone environments where opportunities for transplanting are limited. If only the rainfed lowland and irrigated rice ecosystems are considered, the total direct-seeded area is about 15 million ha. Compared with the 1950s, the importance of direct seeding in irrigated and rainfed lowlands increased during the past three decades mainly in Malaysia, Thailand, and the Mekong Delta (Fig. 1).

Determinants of adoption of alternative crop establishment methods

Generally, water availability and the opportunity cost of labor are the major determinants of crop establishment methods (Fig. 2). A low wage rate and adequate water supply favor transplanting. When the water supply is plentiful and the wage rate is high, the particular method adopted depends partly on the cost of weed control. Economic incentives are likely to be higher for wet seeding when the cost of weed control is low. On the other hand, transplanting may be economically more profitable. Farm-level studies have shown that transplanting tends to be the dominant method in bottom lands where water accumulates from neighboring fields while direct seeding is practiced in higher fields (Pandey and Velasco 1999). Similarly, farmers with smaller families in relation to the size of the farm they manage prefer direct seeding to deal with the labor shortage (Erguiza et a1 1990, Pandey et al 1995).

The transplanting method, although cost-effective in controlling weeds, may not be feasible when water availability is low or uncertain. The traditional system of direct seeding such as *gogorancah* in Indonesia and *aus* and *beushani* in Bangladesh evolved mainly in response to rainfall uncertainty.

Economic incentives for direct seeding increase when labor scarcity and wage rates are high. Much of the recent spread of direct seeding in Southeast Asian coun-

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

Region/ country	Flood-prone + upland rice area	Irrigated + rainfed lowland area	Irrigated + rainfed lowland area direct seeded	Area direct seeded (as a % of irrigated + rainfed lowland area)	Total rice area[b]	Total direct seeded	% of total area direct seeded
South Asia	8.4	47.8	6.3	13.0	56.2	14.9	26.0
Bangladesh	1.9	8.8	0.1	1.0	10.7	2.0	19.0
India	6.5	36.0	5.5	15.0	42.5	12.0	28.0
Pakistan		2.1			2.1		
Sri Lanka		0.9	0.7	78.0	0.9	0.7	77.0
Southeast Asia	4.0	68.2	8.3–10.3	11–14	72.2	12.3–14.3	17–20
Cambodia	0.2	1.7			1.9	0.2	10.0
China	0.5	31.6	1–2.5	3–8	32.1	1.5–3	5–9
Indonesia	1.2	9.8	0.8	8.0	11.0	2.0	18.0
Lao PDR	0.2	0.4			0.6	0.2	33.0
Malaysia	0.1	0.6	0.4	67.0	0.7	0.5	71.0
Myanmar	0.6	5.7			6.3	0.6	9.0
Philippines	0.2	3.4	1.3	38.0	3.6	1.5	42.0
Thailand	0.5	9.1	2.8	31.0	9.6	3.3	34.0
Vietnam	0.5	5.9	2–2.5	34–42	6.4	2.5–3	39–47
East Asia		3.2	0.1	3.0	3.2	0.1	3.0
Japan		2.1			2.1		
Korea		1.1	0.1	9.0	1.1	0.1	9.0
Total	12.4	119.2	14.7–16.7	12–14	131.6	27.3–29.3	21–22

[a]Sources of information on direct-seeded area: Bangladesh—Huke and Huke (1997), S. Bhuiyan, pers. commun.; India—Palaniappan and Purushothaman (1991); Sri Lanka—Pathinayake et al (1991); Cambodia—Helmers (1997); China—Lu Ping, pers. commun.; Indonesia—Huke and Huke (1997) and H. Pane, pers. commun.; Malaysia—Huke and Huke (1997) and own estimate; Myanmar—Huke and Huke (1997) and own estimate; Philippines—PhilRice-BAS (1995) and own estimate; Thailand—Dr. Booribon Somrith, pers. commun. and data from Agricultural Extension Office, Khon Kaen; Japan—Yujiro Hayami, pers. commun.; Vietnam—T.P. Tuong, pers. commun. and Agricultural Statistics of Vietnam (1998); Korea—Kim (1995). [b]Huke and Huke (1997).

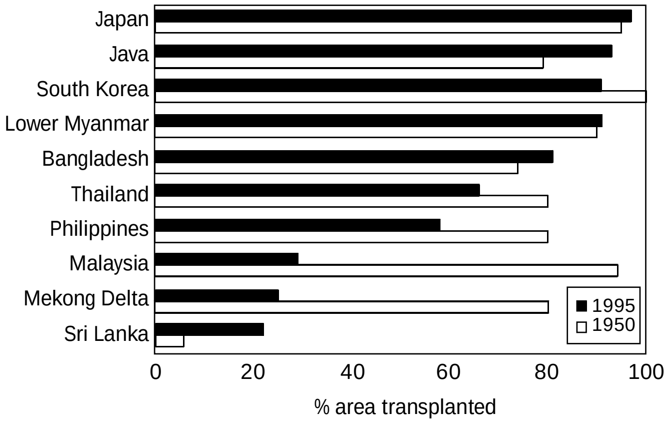

Fig. 1. Changes in rice establishment methods in Asia.

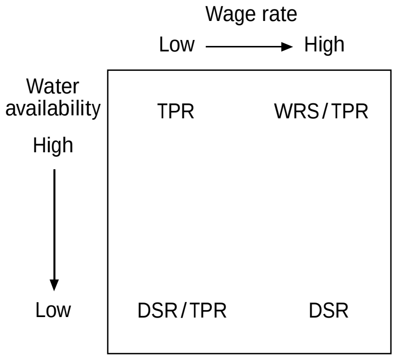

Fig. 2. Hypothesized effects of wage rate and water availability on the choice of crop establishment methods. TPR = transplanting, WSR = wet seeding, DSR = dry seeding.

tries has been in response to the rising wage rate. Even though a switch to direct seeding may have lowered rice yield slightly compared with transplanted rice, farmers have found such a change economically profitable.

Labor scarcity and shifts in crop establishment methods

Historically, two major adjustments in crop establishment methods have been made to deal with rising labor costs. In temperate Asian countries and territories such as Japan, Korea, and Taiwan, the farm labor shortage led to a change from manual to mechanical transplanting (Fig. 3). On the other hand, in tropical countries such as Malaysia and Thailand, the labor shortage induced a shift to direct seeding.

Several factors explain this difference in the way the two groups of countries have responded to labor shortages. Small farm size, a long history of transplanting culture, and a very intensive rice production system in Japan favored the continuation of this practice. In addition, high rice prices that farmers were able to obtain in Japan reinforced the incentive to continue with the transplanting method because a switch to direct seeding may have resulted in income losses due to lower yields. Transplanting may have also helped farmers deal with the low temperature that can adversely affect the performance of direct-seeded rice at higher altitudes. In contrast, Thailand and Malaysia have a much more recent history of transplanting culture. In addition, production in these countries is characterized by a relatively land-extensive agriculture, absence of a temperature constraint for direct seeding, and lower overall average yield and net returns to rice production. Thus, savings in labor cost from direct seeding outweighed the potential loss in income from rice and favored a shift to direct seeding.

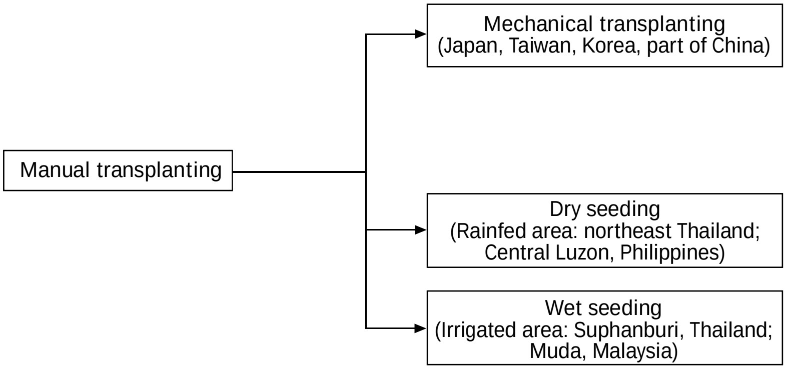

Fig. 3. Alternative patterns of changes in crop establishment methods.

In addition to mechanical transplanting, farmers have used other types of labor-saving methods for transplanting. Farmers in irrigated areas of Laguna, Philippines, use the *dapog* method of seedbed preparation. In this method, seeds are sown on a raised seedbed that is covered with banana leaves, empty bags, or plastic sheets. The covering prevents the roots from coming in contact with the soil. Labor is saved as seedlings transplanted are younger (2 wk old), do not need to be uprooted, and are easily separated during transplanting. Similarly, farmers in some parts of China throw a bunch of 2-wk-old seedlings in the air so that they land scattered on puddled fields. This method can save about 25% on labor cost compared with normal transplanting (Table 2).

Potential advantages and disadvantages of direct seeding

Direct-seeding methods have several advantages over transplanting. First, direct seeding saves on labor (Table 2). Depending on the nature of the production system, direct seeding can reduce the labor requirement by as much as 50%. Second, in situations where 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 *(beusbani)* 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 (Singh et al1994).

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, Singh et al 1994). Direct seeding can also reduce the risk by

Table 2. Preharvest labor use (person-d ha^{-1}) in different countries by crop establishment method.

Country/province	Dry seeding	Wet seeding	Transplanting	Dapog	Seedling throwing
Philippines					
Iloilo[a]	40	30	53		
Pangasinan[b]	22		49		
Laguna[c]				37	
India					
Uttar Pradesh[d]	72	66	112		
Bihar[e]	75		152		
Orissa[f]	141		152		
Tamil Nadu[g]			93		29
Myanmar[f]	19		60		
Vietnam					
Long An[h]	38	38	68		
Indonesia					
Central Java	129[f]–240[g]		75[g]		
Thailand[i]	15		29		

[a]Pandey and Velasco (1998). [b]Pandey et al (1995). [c]Hayami and Kikuchi (2000). [d]Pandey et al (1998). [e]Singh et al (1994). [f]Fujisaka et al (1993). [g]Suyamto and Anwari (1995). [h]Farm survey data. [i]Isvilanonda (1990).

avoiding terminal drought that lowers the yield of transplanted rice, especially if the latter is established late due to 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 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. Finally, irrigation water use can be reduced if direct-seeded (especially dry-seeded) rice 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 et al 1995).

Direct seeding, however, also has several potential disadvantages. The yield of direct-seeded rice under farmers' field conditions tends to be lower than that of transplanted rice (Table 3). Poor and uneven establishment and inadequate weed control are the major reasons for its poor performance (De Datta 1986, Moody 1982). 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 that of transplanted rice. Farm survey data from Iloilo indicated that the weed control cost for direct-seeded rice can be as high as 20% of the total preharvest cost (Table 4). More use of chemical weed control methods in direct-seeded rice can also be potentially damaging to human health and the environment. Other major problems with direct-seeded rice include difficulties in controlling snails and quality deterioration resulting from harvest that may occur during the rainy season.

Table 3. Average rice yield (t ha^{-1}) by crop establishment method.

Site	Dry seeding	Wet seeding	Transplanting
Nueva Ecija, Philippines[a]		4.1	4.3
Iloilo, Philippines[b]	3.7 (1.0)	2.7 (0.9)	3.3 (0.9)
Pangasinan, Philippines[c]	2.7 (1.1)		2.9 (1.2)
Faizabad, eastern India[d]	1.3 (3.7)	1.3 (1.3)	1.6 (0.7)
Long An, Vietnam	4.9	5.0 (0.5)	5.0 (0.3)

Sources: [a]Erguiza et al (1990). [b]Pandey and Velasco (1998). [c]Pandey et al (1995). [d]Pandey et al (1998). Numbers in parentheses are the standard errors.

Table 4. Cost of crop establishment and weed control ($ ha^{-1}), Iloilo, Philippines.

Item	Dry seeding	Wet seeding	Transplanting
Weed control	71	40	24
Labor	51	20	10
Herbicide	20	20	14
Crop establishment			
Labor	17	16	70

Impact of the shift to direct seeding

Although the direct-seeding method has both advantages and disadvantages, its rapid spread in various parts of Asia indicates that the net economic benefit has been positive. Despite a lower average yield, direct-seeded rice has a higher net profit, with the savings in labor cost outweighing the value of loss in output (Table 5). This has occurred especially in areas where labor cost has risen rapidly in relation to the rice price. In addition, total farm income has increased because direct seeding facilitated double cropping of rice in areas where only one crop of transplanted rice would have been grown otherwise. For example, in Iloilo, farmers' income almost doubled as a result of the doubling in cropping intensity made possible by direct seeding. Total labor employment also increased because of crop intensification even though the amount of labor used per crop declined.

The likely future pattern

Despite the rapid spread of direct seeding in several Southeast Asian countries, transplanting remains the dominant method of crop establishment. Because of differences in rice production systems and economic conditions, it is convenient to examine the likely scenario for East, Southeast, and South Asia separately.

In East Asia, where rice production systems are input-intensive, a major shift to direct seeding in response to a further escalation of the wage rate is unlikely to occur.

Table 5. Economic returns ($ ha-1) of different establishment methods in the wet season.

Site	Dry seeding	Wet seeding	Transplanting	% difference
Suphan Buri, Thailand[a]				
Cash cost[b]		152	148	3
Gross returns[c]		505	476	6
Gross margin[d]		353	328	8
Net returns[e]		168	132	27
Pangasinan, Philippines[f]				
Cash cost	230		273	–16
Gross returns	608		666	–9
Gross margin	378		393	–4
Net returns	288		247	17
Iloilo (double-cropped), Philippines[g]				
Cash cost		736	441	67
Gross returns		1,627	904	80
Gross margin		891	464	92
Net returns		695	382	82

[a]Source: Isvilanonda (1990). All values converted to US$ using the exchange rate $1=B20. [b]Cost of all purchased inputs. [c]Gross value of output. [d]Gross value of output minus the cost of purchased inputs. [e]Gross value of output minus the cost of purchased and family-owned inputs. [f]Pandey et al (1995). [g]Pandey and Velasco (1998). Comparison between two crops of wet-seeded rice vs only one crop of transplanted rice.

Compared with other Asian countries, these countries are more industrialized and have higher per capita incomes. Farm incomes are maintained at a higher level through policies that keep the rice price high compared with the international market price. Under this situation, the potential threat to farmer income because of a wage increase is likely to be addressed by policy changes that compensate farmers for a loss in profits rather than by changes in crop establishment method.

Direct seeding is likely to expand further in Southeast Asian countries with low population densities, especially in areas where the labor cost is escalating. Mechanization of land preparation, harvesting, and threshing along with a shift from transplanting to direct seeding are likely to be increasingly adopted. An expansion of irrigation and drainage would further reinforce a shift toward direct (wet) seeding. This type of wage-induced shift, however, is a function of the growth rate of the economy. The recent economic crisis in the region may have slowed down the growth in rural wages and, to a certain degree, may result in some shift back to transplanting. In very densely populated areas such as Java, western China, and the Red River Delta of Vietnam, transplanting is likely to remain the dominant culture.

In South Asia, where population density is high and overall economic growth is slow, economic incentives for a shift to direct seeding are likely to remain weak. The adoption pattern of direct seeding in Southeast Asia shows that it is first adopted in the dry season probably because of better water control than in the wet season. In South Asia, dry-season rice accounts for only about 12% of the total rice area compared with 22% in Southeast Asia. In addition, the overall proportion of rainfed rice area in South Asia is higher. These features of rice systems may contribute to the slower adoption of direct seeding in South Asia. Even when wage rates rise high enough, drainage constraints in rainfed areas may encourage a shift toward mechanical transplanting instead of direct seeding.

Research implications

The primary economic motives for a shift to direct seeding are the savings in labor cost and the possibility of crop intensification. The priority research issue depends on which of the two motives is likely to play a more important role in a particular ecoregion. If the main driving force for the transition to direct seeding is the rapidly rising wage rate, research to generate labor-saving technological innovations would have a high priority. These include mechanical tillage and labor-saving weed control methods. Where drought and early submergence impede the adoption of direct seeding, research to develop varieties and crop management practices to relax these constraints is also needed.

If crop intensification is the major reason for direct seeding, however, research to facilitate early establishment and early harvest of the direct-seeded crop would have a higher priority because this will permit timely planting of the subsequent crop. Developing short-duration varieties would be important in this case. Even though the cost of labor may be low initially in these areas, intensification of land use may lead to labor shortages because of the peak labor demand during the previous crop's harvest and establishment of the succeeding crop within a short period. Suitable mechanical devices for land preparation that can reduce turnaround time between crops could help achieve a higher and more stable yield of the second crop.

The high costs of weed control could be a major constraint to the widespread adoption of direct-seeding methods, especially dry seeding. The key to the success of direct-seeded rice is the availability of efficient weed control techniques. Varieties with early seedling vigor and crop management technologies that help reduce the competitive effects of weeds on crops are needed. It is essential, however, to evaluate the environmental and health consequences of potential technologies that are based on chemical means of weed control.

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" farmer and the average farmer when rice is direct-seeded. A greater variability in the technical efficiency of direct-seeded rice could be partly due to the use of varieties that were originally developed for transplanted culture. Varieties that are specifically targeted for direct-seeded methods could help reduce such yield gaps. Better crop management practices, especially those that facilitate early and more uniform establishment, can be similarly helpful.

Precise water management is a critical factor for high productivity of wet-seeded rice (De Datta and Nantasomsaran 1991). Greater control of water flow on irrigated fields is hence desirable. Most irrigation systems in Asia, however, have been designed to supply water to transplanted rice for which precision in water management is not as critical. Suitable modifications of irrigation infrastructure may not only ensure high yield of direct-seeded rice but also improve water use efficiency. In addition, appropriate mechanical systems of field leveling that ensure uniformity in field-water level are needed.

In dry-seeded rice, land preparation under dry conditions may require mechanical power, especially for hard clayey soils. Large four-wheeled tractors have been used extensively in large flat tracts of northeast Thailand and the Mekong Delta. It is essential to identify the conditions that led to the evolution of rental markets for tractors in these areas so that appropriate policies to develop such markets in other similar areas could be made. Small devices such as power tillers may be more suitable in rainfed areas where fields are too small for effective operations with large tractors.

Although direct seeding is likely to be more widely adopted in the future, transplanting will probably continue to be used, especially in poorly drained rainfed areas. As labor costs rise, farmers would seek labor-saving methods for establishing rice in these poorly drained areas. Without these labor-saving transplanting methods (or heavy investments in drainage), these areas may stop producing rice as labor costs keep rising. Mechanical transplanting could play an important role in these environments, but it is currently not popular in South and Southeast Asian countries.

Research to develop cost-efficient mechanical transplanters that would be more suitable to the farming conditions of South and Southeast Asia could have high payoffs. In addition, other methods of transplanting such as the *dapog* method practiced in irrigated areas of the Philippines and seedling throwing practiced in some parts of China could have high potential returns.

Available evidence indicates that a shift to direct seeding has had a favorable impact on farmer income because it has helped reduce the cost of labor. Where farmers have been able to grow more than one rice crop as a result of direct seeding, the benefits have been even more pronounced. The incomes of landless and marginal farmers, however, could be adversely affected because they are the major sources of hired labor for farm activities including transplanting. If direct seeding leads to an increase in cropping intensity, the net effect on labor demand tends to be positive, as indicated by experiences in Iloilo, Philippines, and the Mekong Delta. If cropping intensity does not increase adequately to fully absorb the displaced labor, or if other nonfarm employment opportunities are not available, direct seeding can have an unfavorable impact on income distribution. Rural industrialization and other policies that help generate additional employment in rural areas may be needed to counteract any negative distributional consequences that may result from a shift to direct seeding.

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Direct seeding of rice in Asia: emerging issues and strategic research needs for the 21st century

V. Balasubramanian and J.E. Hill

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. 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.

Rice is direct-seeded by essentially two methods (dry and wet seeding) based on the physical condition of the seedbed and seed (pregerminated or dry). 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, based on the level of oxygen in the vicinity of the germinating seed or the depth of floodwater at seeding. Seeds may be broadcast or sown in rows on dry/moist/puddled soil, whereas only broadcasting is used for seeding on water.

Direct seeding offers such advantages as faster and easier planting, reduced labor and less drudgery, earlier crop maturity by 7–10 d, more efficient water use and higher tolerance of water deficit, less methane emission, 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 on the

effect of planting or tiller density on weed pressure, pest damage, grain yield, grain quality, harvest index, and crop lodging at maturity to develop management strategies for high-density direct-sown rice in the tropics. Higher resistance to lodging is essential in rice varieties selected for intensive direct seeding to achieve high yields (> 8 t ha^{-1}). Furthermore, varieties must be improved for early seedling vigor, weed competitiveness, tolerance of low oxygen level or submergence, and resistance to drought. We must find practical solutions to alleviate these constraints and to ensure optimum conditions for seeding. Only then will direct seeding become an attractive and sustainable alternative to traditional transplanting of rice.

Direct seeding is becoming an attractive alternative to transplanting (TPR) of rice. Asian rice farmers are shifting to direct seeding to reduce labor input, drudgery, and cultivation cost (De Datta 1986, De Datta and Flinn 1986). The increased availability of short-duration rice varieties and cost-efficient selective herbicides has encouraged farmers to try this new method of establishing rice. It is fast replacing traditional transplanting in areas with good drainage and water control. Appropriate crop management practices are being developed to fully exploit this new technology. This paper reviews direct-seeding methods, assesses crop management practices related to constraints in direct-seeded rice (DSR), and point outs knowledge gaps, if any, for further improving the direct-seeding technology.

Direct-seeding methods and terminology

There are essentially two methods of direct seeding (Table 1), dry and wet seeding, based on the physical condition of the seedbed and seed (dry or pregerminated). Dry seeding is practiced in rainfed lowland, upland, and flood-prone areas. Wet seeding is commonly practiced in irrigated areas. It is further divided into aerobic wet seeding, anaerobic wet seeding, and water seeding, based on the oxygen level in the vicinity of germinating seed. Seeds are broadcast or sown in rows on dry/moist/puddled soil, whereas only broadcasting is used to seed on water. There is a lot of confusion in the terminology used for various direct-seeding practices. It will therefore be useful to have a classification of rice direct-seeding methods as suggested in Table 1, based on seedbed condition, oxygen level around germinating seed, and patterns of sowing.

Dry seeding

The broadcast sowing/row seeding/drilling/dibbling of dry rice seeds on dry (or moist) soil is called dry seeding. Dry direct-seeded rice (D-DSR) is a traditional practice developed by farmers to suit their agroecological conditions (Fujisaka et al 1993, My et al 1995). This is common in most of the rainfed upland or dryland ecosystem, and some areas of the rainfed lowland and deepwater ecosystems. In D-DSR, seeds can be sown before the start of the wet season, permitting the use of early rains for crop establish-

Table 1. Classification of direct-seeded rice systems.

Direct-seeding method	Seedbed condition	Seed environment	Seeding pattern	Where commonly practiced
Dry direct-seeded rice (D-DSR)	Dry soil	Mostly aerobic	Broadcasting; drilling or sowing in rows	Mostly in rainfed areas and some in irrigated areas with precise water control
Wet direct-seeded rice (W-DSR)	Puddled soil	Aerobic/ anaerobic	Various	Mostly in irrigated areas with good drainage
Aerobic wet seeding (Aerobic W-DSR)	Puddled soil	Mostly aerobic	Broadcasting on puddled soil surface; row seeding in open furrows or on flat soil surface	In irrigated areas with good drainage
Anaerobic wet seeding (Anaerobic W-DSR)	Puddled soil	Mostly anaerobic with a thin layer of settling mud; row seeding in furrows and covering with soil	Broadcasting and covering	In irrigated areas with good drainage
Water seeding (DSR on water)	In standing water	Mostly anaerobic	Broadcasting on standing water	In irrigated areas with good land leveling and in areas with red rice problem

ment (Saleh et al 1993, Tuong et al 1993, Rao and Moody 1994, My et al 1995), or up to 30 d after the onset of rains for upland rice (De Datta 1982). After emergence, rice plants grow in upland (aerobic) conditions until harvest (upland rice) or with accumulated standing water in the field for a significant part of the crop cycle in rainfed lowlands (Morris 1982, Denning 1991, Fagi 1993, Saleh et al 1993, My et al 1995). Dry-sown rice converted to flooded paddy 30–40 d after sowing is called semidry rice in Tamil Nadu, India.

Fagi and Kartaatmadja (this volume) noted that rice roots are short and fibrous with dense root hairs in dry soil and long and fibrous with long root hairs in wet soil. When dry-sown rice fields get flooded, rice plants undergo a dry-to-wet transition and leaves turn yellow temporarily, probably because of physiological shock and/or induced N deficiency. They also observed that stem rot is serious in dry-seeded rice in soils deficient in K.

Farmer-perceived benefits of dry seeding are reduced yield risk, improved crop establishment, savings in labor cost, and spread of labor demand (Pandey et al 1995). Other benefits include increased cropping intensity and productivity, the efficient use of early season rainfall and available soil nitrate, reduced water use (700–900 mm rainfall per crop), and lower risk of drought at maturity (Tuong et al 1993, Rao and Moody 1994, My et al 1995, Fagi and Kartaatmadja, this volume). The availability of short-duration rice varieties enhances the chances of double cropping in long wet-season (5–6 mo) areas.

Wet seeding

Wet seeding, specifically aerobic wet seeding, is increasingly practiced in irrigated and favorable rainfed lowlands. Most developed countries establish rice by water seeding because of high wages and scarcity of labor (Smith and Shaw 1966). Farmers in developing countries increasingly adopt wet seeding because of the migration of farm labor to nonfarm jobs and the consequent labor shortage and high wages for manual transplanting (Ho 1995, Pandey 1995, Pingali 1994). Farmers resort to wet direct seeding whenever transplanting is delayed.

Wet seeding offers certain advantages over transplanting:

- faster and easier crop establishment (Rao and Moody 1994),
- less labor needed (1–2 person-d for DSR versus more than 30 person-d for transplanted rice, TPR) and less drudgery,
- earlier crop maturity by 7–10 d (Yoong and Hui 1982, Bhuiyan et al 1995, Vongsaroj 1995),
- higher tolerance of wet (W)-DSR for water deficit conditions in certain soils (Bhuiyan et al 1995),
- a savings in overall production cost and increased profit for farmers (Coxhead 1984, De Datta 1986, Erquiza et al 1990, Awang 1995, Bhuiyan et al 1995, Ho 1995, Jaafar et al 1995, Vongsaroj 1995), and
- less methane emission in DSR: D-DSR < W-DSR < TPR.

There are, however, some problems or constraints associated with wet seeding. In aerobic wet seeding, surface-sown seeds are subject to several abiotic and biotic stresses:

- Damage of surface-sown seeds by birds, rats, snails, etc.
- Desiccation of seeds exposed to direct sunlight or dry weather and disturbance/damage of seeds by torrential rain or flood (Erquiza et al 1990, Bhuiyan et al 1995).
- Increased lodging at maturity because of poor root anchorage on the soil surface (Yamauchi et al 1995).
- Severe competition from rapidly emerging weeds because of the absence of standing water in the first 7–10 d after seeding (DAS).
- Longer occupation of the main field by about 10–15 d and lower yield stability (Yoong and Hui 1982).
- Higher pest and disease incidence because of dense canopy and less ventilation around plants (especially in broadcast-sown rice with high seed rate) (Sittisuang 1995).

Two methods are used for wet seeding: (1) surface or aerobic wet seeding and (2) subsurface or anaerobic wet seeding. The latter includes water seeding.

Surface or aerobic wet seeding. In surface or aerobic wet seeding, pregerminated rice seeds are sown on a well-puddled soil surface 1 to 2 d after puddling. Four different sowing techniques are used in surface seeding: manual broadcasting, broadcasting by motorized duster, spot seeding or dibbling, and drum seeding in rows (Ho 1995, Jaafar et al 1995, Bo and Min 1995).

1. *Manual broadcasting.* This is the most common method used in many developing countries. Pregerminated seeds (24-h soaking and 24-h incubation) are broadcast on the soil surface, 1–2 d after puddling. The puddled soil should be firm enough to keep broadcast seeds partially buried in the soil; mud that is too soft or too dry will kill germinating seeds (Polvatana 1995, Yamauchi et al 1995). If sowing is done on soil with standing water, the field is drained immediately after seeding. The farmer must walk backward and avoid making too many depressions that might collect water and rot the seeds. An experienced farmer can sow 2 ha d^{-1}. Sixty to 100 kg of seed ha^{-1} is enough for broadcasting if the seed is of good quality. However, farmers use 150–200 kg seeds ha^{-1} to guard against poor germination and damage of seeds by biotic and abiotic factors.
2. *Broadcasting by motorized duster.* This is a popular sowing technique in Malaysia (Ho 1995, Jaafar et al 1995). Seeds are soaked for 24 h and incubated for only 12 h to enable seeds that flow well in machines to sprout. The just-sprouted seeds are broadcast over puddled soil with a 5-cm layer of standing water, using a 3.5-hp mist duster attached with either a meter-long blow-pipe or a 20–30-m-long shower blow-pipe. If the farmer has a walking speed of 0.6–0.8 m s^{-1}, the seed rate can vary from 45 to 90 kg ha^{-1} (Jaafar et al 1995). A lower seed rate is applied for high-tillering varieties and a higher seed rate for medium-tillering types (Soo et al 1989).
3. *Spot seeding or dibbling.* Pregerminated seeds (24-h soaking and 24-h incubation) are manually sown on moist soil at predetermined spacing (20 × 20 cm or 25 × 20 cm) (Jaafar et al 1995, Bo and Min 1995). Crop establishment is good with optimum plant density. Weed control is easier in dibbled rice. This, however, is a slow and tedious technique not suitable for large areas.
4. *Row seeding by drum seeder.* The just-sprouted seeds (24-h soaking + 12-h incubation to limit root length) are sown on a puddled soil 1–2 d after puddling, using a perforated drum seeder. A shorter incubation time (12 h) is critical for the easy flow of sprouted seeds from perforated drums. The distance between rows can be easily adjusted. Water should be drained before seeding and the mud should be firm enough to support the seeder and to make shallow furrows for sowing. The seed rate depends on the field condition and the revolution rate of drums, and normally 50–75 kg ha^{-1} is used for drum seeding. It is relatively slower and more tedious than broadcasting and requires 2 person-d ha^{-1}. With wet seeding in rows, farmers can reap additional benefits such as reduced seed rate (50–75 kg ha^{-1} versus 100–200 kg ha^{-1} for broadcast

sowing); better plant arrangement, which facilitates good aeration and light penetration into the canopy, leading to better plant health and less diseases; optimum plant stand (density); easier fertilizer placement between rows; and effective mechanical weeding by rotary or conical weeder.

Anaerobic wet seeding. Sowing of pregerminated rice seeds 5 to 10 mm below the puddled soil surface is called anaerobic wet seeding (Yamauchi et al 1995). Seeds sown beneath the soil surface are less vulnerable to (1) damage by birds and other organisms, (2) disturbance by heavy rains or flood, (3) desiccation by water stress or dry weather, and (4) lodging caused by poor anchorage. Seeds can be broadcast or row-seeded using the anaerobic seeder.

Four different sowing techniques are used in anaerobic wet seeding:

1. *Anaerobic broadcasting*. Pregerminated seeds (24-h soaking and 24-h incubation) are sown immediately after the last puddling. This allows the suspended mud to settle down and form a thin protective cover over the seeds. Seed must be heavy enough to sink below the mud. In this case, there is no need to drain the water before or after seeding. Anaerobic broadcasting can also be practiced by coating seeds with calcium peroxide (Calper), which supplies oxygen to buried seeds (Yamada 1952, Ota and Nakayama 1970).
2. *Anaerobic drum seeding.* Alternately, just-sprouted seeds (24-h soaking and 12-h incubation to limit root length) can be sown in rows 1–2 d after puddling by an anaerobic seeder fitted with furrow openers and closers. There should be no water on the surface at seeding time when using this machine. Seed rates and row spacing can be adjusted to suit local conditions.
3. *Traditional water seeding.* In traditional water seeding, pregerminated seeds (24-h soaking and 24-h incubation) are sown in standing water that recedes with time. Seeds must be heavy enough to sink in standing water to enable anchorage at the soil surface and ensure tolerance not only of low levels of dissolved oxygen and reduced light but also of other stresses, including aquatic seedling ravagers. Seedling establishment is invariably poor because of poor root anchorage and the consequent floating of seedlings (Tuong et al 2000). Water-seeded rice invariably lodges at maturity. Traditional water seeding is resorted to only when early flooding occurs and water cannot be drained from the field. Where the water is clear as in the acid sulfate soils of Pathum Thani Province of Thailand, seedlings can survive and elongate rapidly at a water depth of 3 to 10 cm (Polvatana 1995). Only a few adapted traditional varieties are used for water seeding in parts of Thailand, Indonesia, and Vietnam.
4. *Modern water seeding.* Modern water seeding is the most common wet-seeding method used in temperate zones (Smith and Shaw 1966, Hill et al 1991). It is practiced on 98% of Italian, 81% of Australian, and 33% of United States rice areas (Hill et al 1991). Seeds are mostly sown by aircraft in large fields in the U.S. and Australia or by tractor-mounted broadcast seeders in small fields (< 20 ha) in Italy (Balsari et al 1989). For water seeding, soaked and sprouted seeds are preferred, although dry seeds coated with an inert mixture of talc and a sticker (Hill et al 1991) or calcium peroxide (Lim et al 1991) are used under certain circumstances.

Research findings and strategic issues

Breeding rice varieties for direct seeding

Until now, rice varieties have been specifically bred for transplanted conditions. Some of these varieties perform fairly well under direct seeding. However, rice varieties must be improved for early seedling vigor, weed competitiveness, submergence tolerance to survive untimely rainfall during stand establishment, and drought tolerance to survive dry conditions during germination and later growth stages. Rice varieties selected for wet seeding must have flexible but strong stems to resist lodging at maturity. Other traits such as high yield, good grain quality, and resistance to insect pests and diseases must be retained.

Rice varieties for direct seeding in rainfed systems

Rainfed ecosystems pose several constraints to improving rice yields. Rice varieties bred for both direct-seeded and transplanted rice in rainfed ecosystems must have high yielding capacity and resistance to abiotic stresses (drought, flood, acid soil, low phosphorus) and biotic stresses (weeds, insect pests, diseases) and must be rich in micronutrients (Fischer and Cordova 1998).

Combining molecular breeding with suitable genotypes adapted to water stress conditions common in rainfed areas may provide a solution to the drought problem. For example, Jones et al (1997) have successfully developed fertile interspecific (*Oryza sativa* L. × *O. glaberrima* Steud.) hybrids with high yield potential that are suitable for direct seeding in uplands. They are also being evaluated for rainfed lowlands. The interspecific hybrids exhibit high tillering ability with droopy lower leaves that shade out weeds at early growth, and erect, thick, dark green upper leaves that enhance photosynthetic efficiency at the reproductive stage (WARDA 1999). At the WARDA experiment station (Mbe, upland), the average yields of these hybrids were 3.9 t ha^{-1} with no N applied and 5.9 t ha^{-1} with an application of 80 kg N ha^{-1}. Some of the progenies are resistant to drought at the vegetative and/or reproductive stage (personal communication, M. Jones, WARDA, Bouaké, Côte d'Ivoire, 1999).

Rice varieties for direct seeding in irrigated areas. Plant types meant for direct-seeded flooded rice must possess early seedling vigor and enhanced foliar growth to combat weeds at the vegetative stage, moderate tillering (10–12 tillers), less foliar growth and enhanced assimilate export from leaves to stems during the late vegetative and reproductive phases, sustained high foliar N concentration at the reproductive stage, strong stems to withstand lodging and to store assimilates, and improved reproductive sink capacity with a prolonged ripening period (Dingkuhn et al 1991). Tuong et al (2000) observed that early tillering and canopy development are more important than early seedling vigor to combat weeds in DSR. New plant type lines (improved tropical japonicas) possess some of the above characteristics, but they require further improvement in tillering, grain quality, and resistance to insect pests and diseases as well as lodging. High varietal resistance to lodging is critical to secure high yields in intensive direct-seeded rice systems.

Table 2. Some varieties used for aerobic seeding in different countries.

Malaysia	Thailand	Philippines	Vietnam	Indonesia	India
MR1	RD7	IR64	IR66	Memberamo	IET9994
MR7	RD23	IR10	IR19660	IR64	IET9221
MR27	RD25	IR42	IR32429-47		Vikas
MR71	RD27	IR58	IR9729-67-3		Jalpriya
MR84	KDML105	IR66	IR49517-23		ADT36
TR7	SPR60	IR74	IR50404-57		ASD16
IR42	PSL60-2	C2			BR2655
IR54		C4			
		Korean			

Sources: Malaysia: Ho (1995), Supaad and Cheong (1995); Thailand: Vongsaroj (1995); Philippines: Rao and Moody (1994); Vietnam: personal communication from Cuu Long Delta Rice Research Institute, Omon; Indonesia: personal communication from Research Institute for Rice, Sukamandi; India: DRR (1995, 1996).

Seedling establishment under anaerobic seeding may be controlled by the interaction of environment and management factors (soil properties, temperature, water depth, planting depth, germination conditions), plant physiological characters (tolerance of submergence and anoxia, high elongation ability, and/or resistance to soil stresses), and seed vigor (potential for rapid uniform emergence and development of normal seedlings) (Yamauchi et al 1993). Varieties suitable for anaerobic seeding should have tolerance of anoxia conditions under submergence, rapid seedling growth and high elongation ability, high weed competitiveness, and good seed vigor. Grain yields of several anoxia-tolerant cultivars (PSBRc4, PSBRc10, IR64, IR41996-50-2-1-3, IR52341) were found to be the same as those of high-yielding semidwarf cultivars (Yamauchi et al 1995). Table 2 shows some varieties used for anaerobic seeding.

Rice varieties for water seeding. Although no modern varieties have been developed for this system, some of the anaerobic varieties mentioned earlier can be tried for water seeding. In temperate countries, japonicas are used in extreme latitudes and indicas or japonica × indica cultivars in moderate latitudes (Hill et al 1991). Compared with indicas or japonica × indica cultivars, japonica varieties have a longer coleoptile and radicle and higher dissolved oxygen-use capacity and/or lower oxygen demand during germination underwater.

Lim et al (1991) reported that, for these reasons, percent seedling emergence was higher for japonicas (59%) than for indicas (20%) when seeds were sown 1 cm below the flooded soil surface. In general, short- and medium-grain cultivars (mostly japonicas) have better seedling vigor and are more tolerant of anoxia conditions than long-grain cultivars (Hill et al 1991).

Water management and water productivity

In flooded rice, water is used for land preparation to promote crop growth and to suppress weeds and other pests. The levels of water use and water productivity depend on several factors such as rice variety, season, soil type, duration of land preparation, tillage intensity, method of irrigation, and cultural practices. The extent of savings in water because of direct seeding is highly variable and location-specific. The following are some examples of water management in DSR in both rainfed and irrigated environments.

Water management in rainfed areas. Uneven distribution of rainfall is common in rainfed areas and its effect is highly variable depending on when the water stress or flooding occurs. Supplementary irrigation at critical stages will save a crop and sustain yields in rainfed ecosystems. Soil should not be allowed to dry excessively from the tillering to flowering stage, mainly through life-saving irrigation from farm ponds, if it is available. Thus, digging of farm ponds to collect excess rainwater will be useful not only to save a crop but also to grow fish in the pond. Selection of drought-tolerant varieties, improved dry seeding, and the use of moisture-conserving cultural practices will help improve the sustainability of rice yields in rainfed lowlands (Fischer and Cordova 1998). Further research is needed to determine the best dates of seeding in relation to expected rainfall distribution in different locations. Modern tools such as geographic information systems (GIS) can be used to delineate areas with similar rainfall patterns, which will help extend findings from one site to another.

Water management in wet direct-seeded rice in irrigated areas. Water management is critical in W-DSR, especially during the first 7–10 DAS. During this period, soil should be kept saturated but not flooded to facilitate root and seedling establishment (De Datta 1986, Lim et al 1991, Awang 1995, Ho 1995, Jaafar et al 1995, Pablico et al 1995). However, the absence of standing water in the initial stages encourages the emergence of weeds that compete with rice seedlings. In the Philippines, Tuong et al (2000) demonstrated the conflict among crop stand establishment, early water management, and weed competition in W-DSR. With no herbicide application, water seeding and anaerobic seeding flooded 3 DAS reduced dry weed weight by 73–88% compared with the local farmers' practice of surface seeding with flooding only 10 DAS. However, water seeding could not sustain high rice yields because of poor crop establishment caused by flotation of seedlings. This study also revealed that anaerobic seeding with flooding 7 DAS controlled weeds only under conditions of low weed pressure. In areas with high weed pressure, farmers use preemergence herbicide during crop establishment and control flooding at later stages to manage weeds in W-DSR.

For successful wet seeding, satisfactory drainage is necessary in areas subject to flooding. Proper land preparation and leveling ensure the uniform spread of water during irrigation and facilitate easy drainage when required during crop establishment. With inadequate water control and/or poor drainage, W-DSR may run the risk of early stage submergence and crop failure (Bhuiyan et al 1995). This is why farmers, especially in low-lying areas, avoid direct seeding during the rainy season.

In clay soils (Vertisol), the occurrence of drought with soil cracking soon after seeding may lead to iron deficiency in seedlings, particularly during winter (personal communication: S.V. Subbaiah, Directorate of Rice Research, Hyderabad, India, 1999). Draining of water from the fields in the evening and reflooding in the morning hours may be necessary to maintain adequate soil temperature for good germination and seedling growth at the early stages in areas with low temperature or during the winter season.

Once the crop is established, there is no difference in water management practices for transplanted and direct-seeded rice. The water requirement of rice varies with crop growth stages. For example, a 2-cm water depth is ideal to enhance tillering. Draining the field for 3 d at about 30 DAS will help promote root growth and reduce the development of nonproductive tillers (personal communication: S.V. Subbaiah, 1999). Midseason drainage can shorten the culm and reduce lodging in direct-seeded rice (Kim et al 1999). Data from South Korea (Lee 1995) indicate that lodging was highest under continuous flooding and lowest when fields were drained two times at 20 and 30 d after first flooding or three times at 20, 30, and 40 d after first flooding.

The amount of water saved because of wet seeding is highly variable depending on irrigation method, soil type, duration of land preparation, tillage intensity, and crop management practices. In a comparative study of irrigation service units (ISU) with different methods of crop establishment in Muda, Malaysia, Cabangon et al (this volume) found that dry seeding (DSR) was more water-efficient than wet seeding (WSR) or transplanting (TPR). Mean irrigation water productivity (kg grain m^{-3} of irrigation water) was 1.52 for DSR-ISU, 1.01 for WSR-ISU, and 0.69 for TPR-ISU at yields of 4.3–4.6 t ha^{-1}. In another study in the Philippines, maintaining saturated soil conditions throughout the crop growth period saved more than 40% of irrigation water compared with continuous shallow flooding and produced rice yields as high as those of flooded rice when weeds were controlled by herbicides (Bhagat et al 1999a). Intensive tillage also reduced water loss through percolation and seepage in addition to lessening weed pressure.

Farmers generally maintain a water level of 2–5 cm throughout the crop growth period to favor rice growth and minimize weed pressure. Water stress at the reproductive stage is more damaging to the rice crop than at the vegetative phase. Therefore, the soil should not be allowed to dry excessively from tillering to late flowering. Under limited water supply, wet-seeded rice is reported to be more tolerant of water shortages and hence more efficient in water use than transplanted rice (Bhuiyan et al 1995).

Water management in water-seeded rice. In water-seeded rice in temperate countries, the field is drained 7–10 DAS for a few days to induce rooting activity and harden stems to reduce lodging and then it is reflooded (Lim et al 1991). Complete surface drainage soon after seedling emergence and maintenance of uniform water depth thereafter are critical to facilitating stand establishment in water-seeded rice. Later, rapid drainage and reflooding may be needed to control insect pests, diseases, and/or abiotic stresses (Hill et al 1991).

Nutrient management

Because nutrient management is highly location-specific, no general recommendation is possible for all situations. Cases of fertilizer application for different systems of direct-sown rice are discussed.

Fertilizer use in rainfed areas. Farmers in drought- and/or submergence-prone areas are reluctant to apply fertilizer to direct-seeded or transplanted rice crops because of the highly uncertain weather and yield (Pathinayake et al 1991). The combined use of locally available organic manures and fertilizers will maintain soil fertility and assure fairly high rice yields in rainfed areas. Researchers in India recommend 60 kg N, 13 kg P (30 kg P_2O_5), and 24 kg K (30 kg K_2O) ha^{-1} for medium-tall high-yielding varieties such as Savitri under transplanting or dry-seeding conditions (Samantaray et al 1991). They also advise farmers to incorporate all the P and K and 50% of the N into the soil before seeding and to topdress the remaining 50% of the N at maximum tillering or panicle initiation (PI) if field water conditions permit. Topdressing of N on floodwater results in very high N losses in tropical climates (Mohanty et al 1999). Subsoil banding of NPK fertilizers along with seed is highly efficient in promoting grain yield and nutrient use (Nayak 1996).

Nutrient use and management in irrigated areas. The total amount and time of fertilizer application for W-DSR vary with soil type, inherent soil nutrient status, rice variety, planting season, weather, hydrological conditions, and cropping history. In areas with good irrigation facilities, NPK fertilizer rates range from 60-15-30 kg ha^{-1} for the monsoon season to more than 120-30-60 kg ha^{-1} for the dry season (De Datta et al 1988, DRR 1995, Guong et al 1995, Hung et al 1995). In high-yield environments, grain yields of improved rice varieties can reach 10 t ha^{-1} with adequate fertilization of W-DSR (Garcia et al 1995). In addition to NPK, applying zinc and/or sulfur is necessary in soils deficient in such nutrients (DRR 1995). Zinc deficiency is common in high-pH alkaline soils in plains and organic matter-rich peat soils in highlands. Applying 25 kg ha^{-1} zinc sulfate corrects the deficiency (Savithri et al 1999). A strong N × P interaction in lowland rice has been well demonstrated and grain yield and agronomic N-use efficiency can be maximized only when adequate P is present in the soil (PEM-FAO 1992, Balasubramanian et al 1994, Guong et al 1995).

Split application of fertilizers, especially N and K, is necessary not only to obtain high grain yields but also to minimize lodging and pest incidence in wet-seeded rice. The best split application consists of incorporating half the N plus all the P and K fertilizers into the soil just before seeding or transplanting and topdressing the remaining N at PI over 5-cm-deep floodwater (De Datta 1986). Most farmers in the Philippines apply fertilizers in 2–3 splits from 15–20 to 49 DAS (Rao and Moody 1994). Results of wet-seeding trials conducted in Central Luzon, Philippines (1995 and 1996 dry seasons), indicate that two splits at 21 and 35–42 DAS in row-seeded rice or three splits at 21, 35, and 49 DAS in broadcast-sown rice will optimize both grain yield and agronomic N-use efficiency (IRRI-CREMNET 1998, Balasubramanian et al 2000). Farmers in the Mekong River Delta of Vietnam apply N fertilizer in three equal splits at 10, 25, and 45 DAS (Hung et al 1995). In Malaysia, four splits of N at 20, 40, 55, and 75 DAS are recommended for W-DSR (Awang 1995), whereas in Thailand farmers use two splits at 10–25 and 45–50 DAS (PI stage) (Polvatana 1995). Delaying the first N application until 10 DAS in Vietnam (Hung et al 1995) and until 30 DAS in Malaysia (Supaad and Cheong 1995) and Thailand (Vongsaroj 1995) did not decrease yields.

If excess N is applied to flooded rice crops, plants could become more susceptible to fungal diseases and insect damage. This is aggravated under direct-seeding conditions where canopy density is invariably high. Reissig et al (1985) observed that the dense canopy of direct-sown rice provides an ideal condition for the multiplication of brown planthopper. Further research is needed to establish the effect of regulated N application on pest incidence in direct-sown rice.

High variability in soil N supply requires field-specific, variable-rate N application in transplanted or direct-seeded rice. Using the chlorophyll (SPAD) meter or leaf color chart (LCC), it is possible to optimize grain yields with high N-use efficiency in W-DSR. Plant density as determined by crop establishment method influences SPAD readings. In the Philippines, a SPAD critical value of 35 optimizes grain yield for TPR with a productive tiller density of 450–500 m^{-2} in the dry season. When the same threshold was used for W-DSR, N rates were high and grain yields were low (Balasubramanian et al 1999).

Under Philippine conditions, a SPAD threshold of 29 was found to be optimum for broadcast W-DSR with around 800 productive tillers m^{-2} (grain yield = 6.8 t ha^{-1} in the 1997 dry season) and 32 for row W-DSR with 650 productive tillers m^{-2} (grain yield = 6.8 t ha^{-1} in the 1997 dry season) for both the wet and dry seasons (IRRI-CREMNET 1998, Balasubramanian et al 2000). It was observed earlier that foliar N concentration in broadcast-seeded rice was less than that of TPR at all growth stages irrespective of N level applied (Peng et al 1996). This could be due to excessive vegetative growth resulting in dilution of plant N (N-deficient canopy) when semidwarf varieties developed for transplanting are sown directly on puddled soil (Dingkuhn et al 1991). Thus, the critical SPAD value is inversely related to plant or tiller density. We expect critical SPAD values of 30–32 for high-density (650–800 productive tillers m^{-2}) and 33–35 for medium-density (400–500 productive tillers m^{-2}) direct-seeded rice (Balasubramanian et al 2000). Further research is needed to validate suggested critical SPAD values for rice sown at different densities.

Modified urea materials such as sulfur-coated urea, urea briquette, and urea super granule were found to be superior to the best split application of prilled urea for flooded rice (De Datta 1985). Placement of urea tablets (UT) at 5–10-cm depths has been shown to increase grain yields and agronomic N-use efficiency in transplanted rice (Balasubramanian et al 1999, Mohanty et al 1999, Pasandaran et al 1999). However, farmer adoption is low because of the additional labor needed for deep placement. Moreover, deep placement of UT is possible only in row-seeded rice.

Controlled release fertilizers (CRF) are materials that release nutrients at rates and concentrations that match the needs of crops at specific growth stages for maximum efficiency. If a single basal application of CRF in flooded rice will synchronize N supply with crop demand, it is expected to increase grain yield and plant uptake of N, minimize various N losses, and reduce fertilizer-related pollution of the environment (Shoji and Gandeza 1992). CRFs from two sources were evaluated in wet-seeded rice in the Philippines during 1997 and 1998. Grain yields were low in the 1997 and 1998 wet season because of poor water control. During the 1998 dry season, grain yields were low because of low panicle density (341–425 m^{-2}) as a result of water stress caused by the El Niño phenomenon. Our experience shows that high yields and N-use efficiency require a panicle density of 750–800 m^{-2} in broadcast-sown rice and 550–650 m^{-2} in row-seeded rice. Despite low yields, CRFs were more efficient than split application of prilled urea, with a savings of 33–50% in N fertilizer use. Further evaluation of CRFs under direct seeding continues in farmers' fields in different countries to ascertain their technical and economic efficiency as well as acceptability by farmers.

In temperate countries, 100–200 kg N, 20–30 kg P, and 40–60 kg K ha^{-1} are generally applied on dry- or water-seeded rice. The N application rate is highly location-specific and dependent on a prerice crop in the rotation. P and K are incorporated into the soil before planting, whereas N is applied just prior to permanent flood at the 3-leaf or early tillering stage (Humphreys et al 1987). Preflood N broadcast on dry soil and incorporated by tillage or by floodwater gave the highest yields in water-seeded rice under conventional tillage in Arkansas, USA (Norman et al 1988). In no-till water-seeded rice, preplant N incorporated by floodwater produced the highest yields (Bollich et al 1996). However, this is not a suitable option for areas with early season algae problems in rice fields. Wherever zinc deficiency occurs, it is corrected by applying 8–16 kg Zn ha^{-1} (Hill et al 1991).

Weed management

Weed flora and weed recruitment under direct seeding. Under direct seeding, weeds are the biggest biological constraint in all but water-seeded rice because they emerge simultaneously with rice seedlings because of the absence of flooding in the early stages. Generally, weeds such as grasses, sedges, and broadleaf weeds are found in D-DSR fields. The dominant weeds in D-DSR fields are *Echinochloa crus-galli* and *Leptochloa chinensis* among grasses, *Cyperus difformis* and *Fimbristylis miliacea* among sedges, and *Ammania baccifera*, *Eclipta prostrata*, and *Sphenoclea zeylanica* in the broadleaf category. Table 3 lists examples of dominant weeds of W-DSR in some Asian countries.

Weed pressure is often two to three times higher in D-DSR than in transplanted crops. It is commonly observed that dry direct seeding is subject to relatively more weed pressure than wet direct seeding, probably because of differences in land preparation. Grassy weeds such as *E. crus-galli*, *E. colona*, and weedy rice (*Oryza* spp.) dominate the weed flora under continuous wet seeding. They closely resemble rice seedlings and thus it is difficult to differentiate such weeds and remove them in the early growth stages. The weed species *Paspalum distichum* and *E. colona* may become dominant in rice grown under zero tillage. Reported yield losses from weeds on D-DSR range from 20% to 88% in India (DRR 1995), 40% to 100% in South Korea (Park et al 1997), and 36% to 56% in the Philippines (De Datta 1986, Rao and Moody 1994). Similar weed-related yield losses occur in other countries. Weedy rice is a serious problem in temperate countries because the red pericarp spoils the appearance and market value of cultivated rice (Smith 1981).

Weed management strategies in direct-seeded rice. Cultural practices and manual, mechanical, and chemical methods are used to manage weeds in direct-seeded rice.

Table 3. Dominant weed species in direct-seeded rice in different Asian countries.[a]

Weed species	Malaysia	Philippines	Thailand	Vietnam	India
Grasses					
Echinochloa crus-galli (L.) Beauv.	**	** (RF,IR)	**	**	**
E. glabrescens Munro ex Hook. f.	**	* (RF,IR)	–	**	
E. oryzoides	**	–	–	–	
E. colona (L.) Link	*	* (RF)	*	–	**
E. picta	–	** (IR)	–	–	
E. stagnina	–	** (IR)	–	–	
Oryza spp. (L.) (weedy rice)	**	–	**	*	
Leptochloa chinensis (L.) Nees	**	–	**	–	*
Ischaemum rugosum Salisb.	*	** (RF)	–	–	*
Paspalum paspaloides	**	–	–	–	
P. distichum (L.)	–	** (RF,IR)	–	–	
Eleocharis dulcis (Burm. f.)	–	–	*	–	*
Cynodon dactylon (L.) Henschel	–	* (RF)	–	–	*
Broadleaf weeds					
Ammania baccifera L.					**
Monochoria vaginalis (Burm. f.) Presl	**	** (RF,IR)	–	–	
Sagittaria guyanensis	**	–	–	–	
Ludwigia adscendens	**	–	–	–	
L. octovalvis (Jacq.) Raven	–	* (IR)	–	–	
L. perennis	–	* (IR)	–	–	
Marsilea crenata Presl	*	–	**	–	
M. minuta	–	–	–	–	
Sphenoclea zeylanica Gaertn.	*	* (RF,IR)	**	–	**
Limnochoris flava	*	–	*	–	
Ipomoea aquatica	–	* (IR)	–	–	
Eclipta alba L.	–	–	*	–	
Eclipta prostrata L.					**
Jussiaea linifolia Vahl	–	–	**	–	
Pseudoraphis spinescens	–	* (RF,IR)	–	–	
Sedges					
Fimbristylis miliacea (L.) Vahl	**	** (RF,IR)	**	**	*
Cyperus difformis L.	**	* (RF,IR)	**	–	**
C. iria L.	–	** (RF,IR)	*	–	
C. rotundus L.	–	** (RF,IR)	–	–	
Scirpus grosus L.	**	–	–	–	
S. supinus L.	–	** (IR)	–	–	
References	Ho (1995), Lo and Cheong (1995)	Rao and Moody (1994), Bhagat et al (1999b)	Vongsaroj (1995)	CLRRI (personal communi-cation)	DRR (1995)

[a]– = not important, * = important, ** = very important, RF = rainfed ecology, IR = irrigated ecology.

The selection of weed-suppressing rice varieties and use of clean seed are the basis for reducing weed pressure in any rice system. Some farmers use repeated plowing at 7–10-d intervals to uproot emerging weeds and to prepare clean seedbeds for sowing. Farmers in the Philippines and Vietnam use high seed rates to suppress weed pressure at the early stages. Labor is used to remove weeds manually in broadcast-sown or row-seeded rice and mechanical weeding with an interrow cultivator is possible only in row-seeded crops. Manual weeding requires a minimum of 20 and a maximum of 103 person-d ha^{-1} (Fujisaka et al 1993, My et al 1995). Herbicides can be used to kill weeds wherever they are appropriate and economically attractive.

Good land preparation and leveling, the selection of weed-competitive varieties, the use of clean weed-free seeds, proper water management (fewer weeds in continuously flooded fields), and intensive multiple cropping will help reduce weed pressure in W-DSR (Vongsaroj 1995). Breaking the wetland cycle with a dryland crop helps prevent the buildup of a particular weed species (Ahmed and Moody 1982). For example, rotating soybean after rice minimizes the *E. crus-galli* problem in Thailand (Vongsaroj and Price 1987).

Some farmers wet fields initially and allow weeds to germinate for about 7 d. Then, they uproot the weeds by plowing and flood the field for another 7–10 d to kill the initial flush of weeds. They then puddle and level the soil for wet seeding. In areas with severe weed infestation, weeds are allowed to germinate with a flush irrigation and are killed by spraying glyphosate (3.5 L ha^{-1}) 10 to 15 d after wetting the soil. When the initial weed flush is killed, the field is then puddled and leveled for wet seeding. This is called stale seedbed preparation for direct wet seeding of rice.

There is a strong conflict among crop stand establishment, early water management, and weed competition in W-DSR (Tuong et al 2000). When no herbicide was applied, *Echinochloa glabrescens* dominated the weed flora in surface-seeded plots with no standing water for the first 10 DAS (farmers' practice) and under anaerobic seeding with flooding at 7 DAS. However, when the flooding was advanced to 3 DAS in anaerobic-seeded plots, the relative abundance of *Monochoria vaginalis* increased over that of *E. glabrescens*. Water seeding controlled grassy weeds effectively, but could not sustain high rice yields because of poor stand establishment. Anaerobic seeding with flooding 3 DAS maintained high yields with half of the recommended herbicide rate or without herbicide application. Seeding method, flooding time, rice genotype, and herbicide use have to be manipulated to suppress weeds under wet seeding.

If manual weeding is practiced, a minimum of two hand weedings at 15–20 and 30–35 DAS will be needed. Manual weeding is difficult in broadcast-sown rice because of high plant density and the problem of differentiating grassy weeds, especially *E. crus-galli, L. chinensis,* and weedy rice, from rice plants (Vongsaroj 1995). Manual weeding requires a minimum of 20 and a maximum of 103 person-d ha^{-1} (Fagi 1993, Fujisaka et al 1993). If the crop is planted in rows, rotary (in sandy to sandy loam soils) or conical weeders (in clayey soils) can be used to control weeds, using 8 to 12 person-d ha^{-1} for two operations.

Many rice farmers apply preemergence herbicides to kill weeds in the early stages and then use standing water to suppress weed growth in the later stages. During herbicide application, a thin layer of water is maintained on the soil surface to evenly spread the herbicide over the entire field. Herbicide trials conducted in India showed that butachlor + safener at 1 kg ai ha^{-1}, pretilachlor + safener at 0.4 kg ai ha^{-1}, and anilophos + trichlopyr at 300 + 200 g ai ha^{-1} controlled a broad spectrum of weeds in wet direct-seeded rice and produced a grain yield equivalent to that of hand weeding two times (personal communication: S.V. Subbaiah, Directorate of Rice Research, Hyderabad, 1999). A new formulation of pyriftalid/cinosulfuron has been developed for splash application at 6–8 DAS in wet-sown rice to control a wide array of weeds (Lojo et al 2001). Thus, for effective weed control with herbicides, selection of the right herbicide or herbicide combination, application at the recommended rate and time, and maintenance of proper field conditions for herbicide application are vital. Table 4 provides the recommended rates and times of application of selected herbicides for direct-seeded rice.

Continuous application of the same or similar herbicides may lead to infestation of selective tolerant weeds, especially the difficult-to-control perennial weeds (Ho 1995, Lo and Cheong 1995, Rao and Moody 1994, DRR 1995). The emergence of propanil-resistant barnyard grass and weedy rice or "padi angin"(*Oryza* spp.) under continuous wet direct seeding was reported in Malaysia (Lo and Cheong 1995).

Table 4. Recommended rates and time of application of selected herbicides and their specificity/requirements (Sources: Lo and Cheong 1995, Vongsaroj 1995, Lojo et al 2000).

Herbicide	Dose (kg ai ha^{-1})[a]	Time of application (DAS)	Remarks
Pretilachlor	0.5–1.0	0–4	Moist soil with a thin film of water, flood 5–10 d after application
Pretilachlor + safener	0.5	6–10	Moist soil with a thin film of water, flood 5–10 d after application
Thiobencarb	2.0	6–10	Moist soil, flood 4–5 d after application
Thiobencarb/propanil	1.0/0.5	5–7	Moist soil, flood 4–5 d after application
Butachlor	0.75–1.00	6–10	Moist soil, flood 4–5 d after application
Piperophos/2,4-D	1.0/0.5	6–10	Moist soil, flood 4–5 d after application
Bifenox	2.0	6–10	Moist soil, flood 4–5 d after application
Pyriftalid + cinosulfuron	0.115–0.150	6–8	Splash-apply on floodwater or spray on drained soil surface
Oxadiazon/2,4-D	0.5/0.5	9–12	Flood water, maintain water for 14 d after treatment
Oxadiazon	0.75	6–12	Flood water, maintain water for 14 d after treatment
EPTC/2,4-D	3.0/0.5	10–14	Flood water, maintain water for 14 d after treatment
Molinate	3.0	10–14	Flood water, maintain water for 14 d after treatment
			Poor control of broadleaf weeds and *I. rugosum*
Propanil	2.5	10–14	Drain field, reflood 3–5 d after treatment
Propanil/molinate	2.0/2.0	10–14	Drain field, reflood 3–5 d after treatment
Propanil/thiobencarb	2.0/2.0	15–20	Drain field, reflood 3–5 d after treatment
Propanil/2,4-D	2.0/0.5	15–20	Drain field, reflood 3–5 d after treatment
2,4-D	0.50–0.75	15–20	Not for grasses
Fenoxaprop	0.06	25–35	Dry or flooded field; if dry soil, irrigate 3–4 d after treatment; no effect on broadleaf weeds, sedges

[a]ai = active ingredient, DAS = days after seeding.

Similarly, *Phalaris minor* is becoming resistant to herbicides in the rice-wheat system in South Asia. Herbicides should be changed periodically and/or used minimally together with other methods of weed control.

Integrated weed management (IWM) requires a good combination of appropriate rice varieties, crop husbandry practices, and other weed control techniques to effectively manage weeds in direct-seeded rice. To be efficient, IWM practices should be dynamic and should involve crop rotation, crop establishment methods, and/or the use of herbicides.

Pest and disease management

Compared with TPR, the outbreak of insect pests and diseases is more severe in W-DSR because of high plant density and the consequent cooler, more humid, and shadier microenvironment inside the canopy. The major insect pests of W-DSR are BPH, stem borer, green leafhopper, leaffolder, and gall midge. Important diseases that affect W-DSR are blast, ragged stunt virus, yellow orange leaf virus, sheath blight, and dirty panicle (Pongprasert 1995). Other insect pests that attack emerging rice seedlings are the golden apple snail (*Pomacea canaliculata* [Lamarck]) and rats. Protecting young seedlings against these pests is more difficult in W-DSR than in TPR. In the Philippines, farmers make narrow ditches to entice snails to pools of water and then handpick them. In severe cases, molluscicides are used to control snails. Indonesian farmers report that the rat problem is more serious in W-DSR than in TPR, especially in broadcast-sown crops. They use traps, barn owls (biological predator), and sulfur fumigation or poison baits to minimize rat damage.

Cultivation of resistant varieties can complement cultural practices to reduce pest problems under wet direct seeding. There are varieties resistant to or tolerant of BPH, ragged stunt virus, blast, and bacterial leaf blight, but none for stem borers, thrips, leaffolder, sheath blight, sheath rot, and dirty panicle (Pongprasert 1995).

Integrated pest management (IPM) is a strategy that employs various tactics or control measures harmoniously to bring the pest population below the economic threshold level. Adoption of the IPM strategy by combining resistant varieties, predator management, cultural practices, and/or the judicious application of pesticides will help control most insects and diseases (Heong et al 1994, 1995).

Management of crop lodging

Crop lodging at maturity is a serious problem with surface-seeded rice, especially under wet seeding including water seeding. Shallow root establishment and thin, long stems are the main factors responsible for lodging in surface-seeded high-density crops. In addition to high plant density, the rate and time of N application and level of floodwater and mid-season drainage of the field determine lodging severity. Crop lodging, if severe, makes harvesting by machines difficult. Grain losses are high and grain quality is poor in badly lodged crops even if they are harvested manually.

Lodging caused by the bending of stems is common in TPR, whereas root lodging is severe in D-DSR (Kim et al 1993). Kim JK et al (1995) have observed that lodging-resistant rice varieties possess thicker and deep-penetrating roots, bigger culms with thick walls, and erect stems and leaves that allow light penetration to the lower canopy. Cultural practices that could minimize lodging in D-DSR include using an appropriate seed rate, subsurface or anaerobic seeding, adjusting the rate and time of N application (Kim CK et al 1995), and practicing midseason drainage. Midseason drainage can shorten the culm and reduce lodging in D-DSR (Kim et al 1999). Data from South Korea (Lee 1995) demonstrated that lodging was highest under continuous flooding and lowest when fields were drained twice at 20 and 30 d after first flooding or three times at 20, 30, and 40 d after first flooding.

Research needs

Crop growth and yields of direct-seeded rice can be further improved by using specifically bred rice varieties resistant to lodging and improving certain crop management practices. Additional research is needed in crop lodging, water management, nutrient management, weed ecology and management, and management of high planting or tiller density.

Crop lodging

Crop lodging is an important issue that needs further research attention to improve the direct-seeding technology. Research in South Korea has shown that factors such as rice variety, tillage, crop establishment method, seeding rate and plant density, total amount and method of N application, and midseason drainage can be manipulated to minimize lodging in direct-seeded rice (Kim JK et al 1993, 1995, 1999, Kim CK et al 1995, Lee 1995). These areas need to be studied in the tropics to understand and mitigate the lodging problem under direct seeding. Further, rice varieties with resistance to lodging must be developed to achieve high yields in intensive direct-seeded rice systems.

Water management

Research data on water management in direct-seeded rice are highly location-specific. General principles of water management derived from earlier studies have to be used ingeniously to develop suitable irrigation practices for new situations. Further research is needed on the long-term effect of zero or minimum tillage (nonpuddling) on seepage and percolation losses of water under different types of irrigation. The implications of resource substitution, such as the use of herbicide in place of water to control weeds in rice fields, are not fully understood.

Nutrient management

Excessive vegetative growth at the early stages, N-deficient canopies at the reproductive phase, and premature leaf senescence could limit the efficiency of photosynthesis and crop yields in direct-seeded rice. Nitrogen management in the post-PI stage is critical for improving photosynthetic efficiency and grain production in irrigated DSR. Another research issue is to understand how the regulated N supply based on crop demand affects the incidence of insect pests and diseases (BPH, sheath blight, blast) as well as crop lodging at maturity.

Weed ecology and weed management

The ongoing research on weed ecology will enhance knowledge and understanding of the recruitment and evolution of weed species under different crop establishment methods (dry, wet, and zero-tillage direct seeding in relation to transplanting), which will help us develop new weed management strategies. We also need to study the effects of rotating crops and crop management practices, including crop establishment methods and herbicides, on the evolution of weeds and the stability of grain yields over time.

Managing high plant density and its effect on weeds, insect pests, and diseases

High planting density with resulting high vegetative biomass is adopted in direct seeding to suppress weeds and to obtain high yields. Observed panicle densities are 700–800 m^{-2} in broadcast-sown rice and 500–600 m^{-2} in row-seeded rice in tropical developing countries, compared with >1,200 m^{-2} in temperate Australia. High tiller density leads to highly humid microenvironments in the rice canopy that might favor the invasion of certain pests and diseases. Research data are lacking on the effect of planting or tiller density on weed pressure, pest damage, grain yield, grain quality, harvest index, and crop lodging at maturity.

Developing technology packages for direct-seeded systems

Most of the problems and issues discussed earlier are discipline-oriented and most of the factors are interrelated and interact with each other. For example, management of irrigation water will affect the severity of weed and pest infestation and the efficiency of fertilizers and pesticides. Thus, an interdisciplinary research effort is vital to develop viable packages of technologies for different direct-seeded rice systems.

Summary and conclusions

Direct seeding could be an attractive alternative to transplanting of rice. It is expected to minimize labor input and reduce cultivation cost. Essentially, there are two methods of direct seeding of rice, dry and wet seeding, based on the physical condition of the seed and seed environment. Wet seeding is further divided into aerobic wet seeding, anaerobic wet seeding, and water seeding, based on the oxygen level in the vicinity of germinating seeds. Rice seeds are broadcast or drilled in rows on dry, moist, or puddled soil, whereas only aerial or mechanical broadcasting is practiced in water seeding.

Component technologies are being developed for managing direct-seeded rice. The interaction is strong among land leveling, irrigation, weed management, and input-use efficiency. Location-specific synergistic combinations of technology options have to be identified and used to maximize economic returns to farmers and environmental benefits to the community.

Further research is needed on managing N inputs during the post-PI stage to improve photosynthetic efficiency and grain production and to attain yields above 8 t ha^{-1} in direct-seeded rice. The effect of plant density on the severity of weed problems and pest damage, grain yield, grain quality, harvest index, and lodging at maturity requires further study. Research on various factors affecting crop lodging is vital to improving the direct-seeding technology. A special rice breeding program should focus on developing specific rice varieties for direct seeding with early seedling vigor, drought and submergence tolerance, thick and deep-penetrating roots, and strong culms/stems to resist crop lodging at maturity.

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Patterns and processes in direct seeding

Gogorancah rice in Indonesia: a traditional method in the modern era

A.M. Fagi and S. Kartaatmadja

Indonesia's successful increase in rice production has been attributed to the use of improved varieties, application of adequate fertilizers, and intensive pest and weed control. Considerable development and rehabilitation of the irrigation infrastructure have made it possible to expand area planted to rice and implement modern crop management. This paper reviews the origin of the *gogorancah* system of rice production, its successful adoption, and research to further improve that technology. Traditional techniques of land preparation, seedling establishment, and water management from rainfed systems were combined with cultivar choice and nutrient and weed management used for modern, high-yielding rice varieties to increase rice productivity and cropping intensity and to sustain rice production in rainfed systems. A successful trade-off between the traditional and modern rice cultivation systems in rainfed rice areas resulted in great success through a massive campaign by the government. The *gogorancah* technique has been practiced successfully by farmers in flooded rice, where the crop can be submerged at maturity. With this technique, mature panicles could be harvested before deepwater submergence occurred. The subsequent expansion of *gogorancah* in nonpuddled, bunded fields has become a national agenda in the rice intensification program. Results demonstrate that the *gogorancah* technique is a scientifically sound method of rice cultivation from the agronomic and physiological points of view.

In the rainfed environment of some parts of Java and Madura, a method of rice cultivation known as *gogorancah* is practiced in which no nursery beds are used. The oldest record of the *gogorancah* system dates back to 1905, but studies on this system began in 1922-27 to improve the technology.

The largest areas of rainfed lowland rice fields are in Java, North Sumatra, and South Sulawesi, with a total of 1.3 million ha (Amien and Las 2000) out of 2.6 million ha of rainfed lowland rice in Indonesia (Fagi and Syamsiah 1991).

Experienced rice farmers invented the *gogorancah* system because

- Puddling of soil, which consists of one plowing operation or more followed by harrowing and leveling, requires a relatively long time.
- Land soaking prior to wet plowing and regular wetting to soften the soil for harrowing and leveling needs plenty of water; with this kind of soil treatment, farmers have to wait for heavy rains until the soil impounds enough water; consequently, planting is done late in the season.
- Late planting, because of using the transplanting technique, often leads to water stress during the reproductive stages of growth, with a consequent yield loss.

Soil cultivation for *gogorancah* rice takes place without water. Light tillage is done in the dry season to a depth of 12–15 cm. It is followed by a second tillage at the beginning of the wet season or a few weeks before the wet season starts. Rice seeds are dibbled or broadcast on pulverized dry soil.

Rice plants grow in aerobic or unfloodeds condition for the first 5–6 wk after seed germination, despite some initial heavy rain. Subsequently, the soil is converted into anaerobic, flooded conditions throughout most of the growing period by impounding an increasing amount of rainwater in the field. If the amount of rainwater is less than expected, the soil may remain in a dry and aerobic condition up to harvesting, as is the case in dryland or upland rice (Giessen 1942).

Starting in the First Five-Year Development Plan (1969–73), the *gogorancah* system became a focus of the rice intensification campaign, particularly in regions where the onset and withdrawal of rainfall are unpredictable. Survey results in target areas of *gogorancah* rice intensification showed that local rice varieties planted under the traditional *gogorancah* technology yielded 1.8–3.1 t ha^{-1}, whereas improved rice varieties with modern technology planted in the same way yielded 4.0–6.1 t ha^{-1}. Improved cultivars were able to take advantage of earlier sowing and the extra water made available to the crop. In *gogorancah*, seeds are broadcast or row-seeded right at the beginning of the wet season. If transplanting is used, rainfall is not adequate to puddle the soil until later, and the crop cannot access rainfall from that period. Further, if rain stops for a few days, the soil will be hard and unfavorable for the penetration of young roots, particularly on heavy-textured soils (GAMA 1973, UNIBRAW 1973, UNPAD 1973).

Agronomists introduced the *gogorancah* system to irrigated areas in the lowland plain of the fluxial part of Indramayu District, West Java, in 1977. Late planting of rice because of the long soil puddling process, commonly practiced by farmers in that area, subjects the rice crop to flood during its reproductive growth stage. In this part of the rice area, water depths of more than 1 m are common late in the wet season, which coincides with the maturity stage of the rice plant. By using the *gogorancah* technique, rice seeds are planted earlier on well-pulverized soil and mature panicles can be harvested before they are covered by water (Fagi et al 1986, Suryatna et al 1979).

Lessons learned from the successful campaign of the *gogorancah* system in Indramayu District were introduced to underdeveloped rainfed rice areas on Lombok Island, West Nusatenggara, in the 1980-81 wet season. This island has an annual rainfall of 1,330 mm (average of 30 y), distributed irregularly within 3-4 mo (Fig. 1). The limited period of available rainwater is aggravated by soil puddling, the traditional method of land preparation for transplanted rice. Because of late planting, the rice crop is subjected to dryness during its reproductive growth stage, resulting in low grain yield and sometimes causing complete harvest failure. This happened for many years, making rice production on the island low; hence, it could not meet the demand for rice. The *gogorancah* rice intensification program begun by the government in the 1980-81 wet season increased rice productivity and stabilized production, and has turned Lombok Island from a critical food-short system to a food-surplus production system. Since then, this island has exported rice to the surrounding islands.

Factors affecting grain yield of *gogorancah* rice

Rice varieties

The conversion of soil water regimes of a *gogorancah* rice field from dry to wet conditions 5–6 wk after seed germination results in a very radical change in the growth of the rice plant. During the dry stage (oxidized soil condition), a dry root system is formed, characterized by short fibrous roots and vigorous development of lateral roots, which are densely covered with root hairs. When the field is flooded (reduced soil condition), all dry roots gradually die and a wet root system is formed, distinguished by long, straight, fibrous roots, and often long hair roots emerge, while few, if any, root hairs exist (Giessen 1942).

The 5–6-wk period after seed germination is the active vegetative growth stage of short-duration, high-yielding, improved rice varieties. The transition period in the root system in most cases is indicated by a stagnant growth and by the yellowish color of the leaves. Therefore, the soil water regime should not be converted when rice plants are younger than 5 wk and older than 10 wk (panicle initiation or PI stage); for medium-growth duration varieties, PI may occur 7 wk after transplanting or 10 wk after seeding. If heavy rain occurs after 10 wk, the soil must be kept under aerobic conditions. Flooding before 5 wk of age will result in fewer panicles per hill and, consequently, fewer spikelets per panicle or high spikelet sterility. Under aerobic soil conditions, the rice plant will produce an aerobic root system; when the field is submerged, a new root system adaptable to unaerobic soil conditions will emerge, whereas the former gradually dies. The transition period should not occur when the rice plant is too young or at the panicle differentiation stage. Applying nitrogen before the transition period may lessen the yellowish color of rice leaves, but this has not been adequately tested.

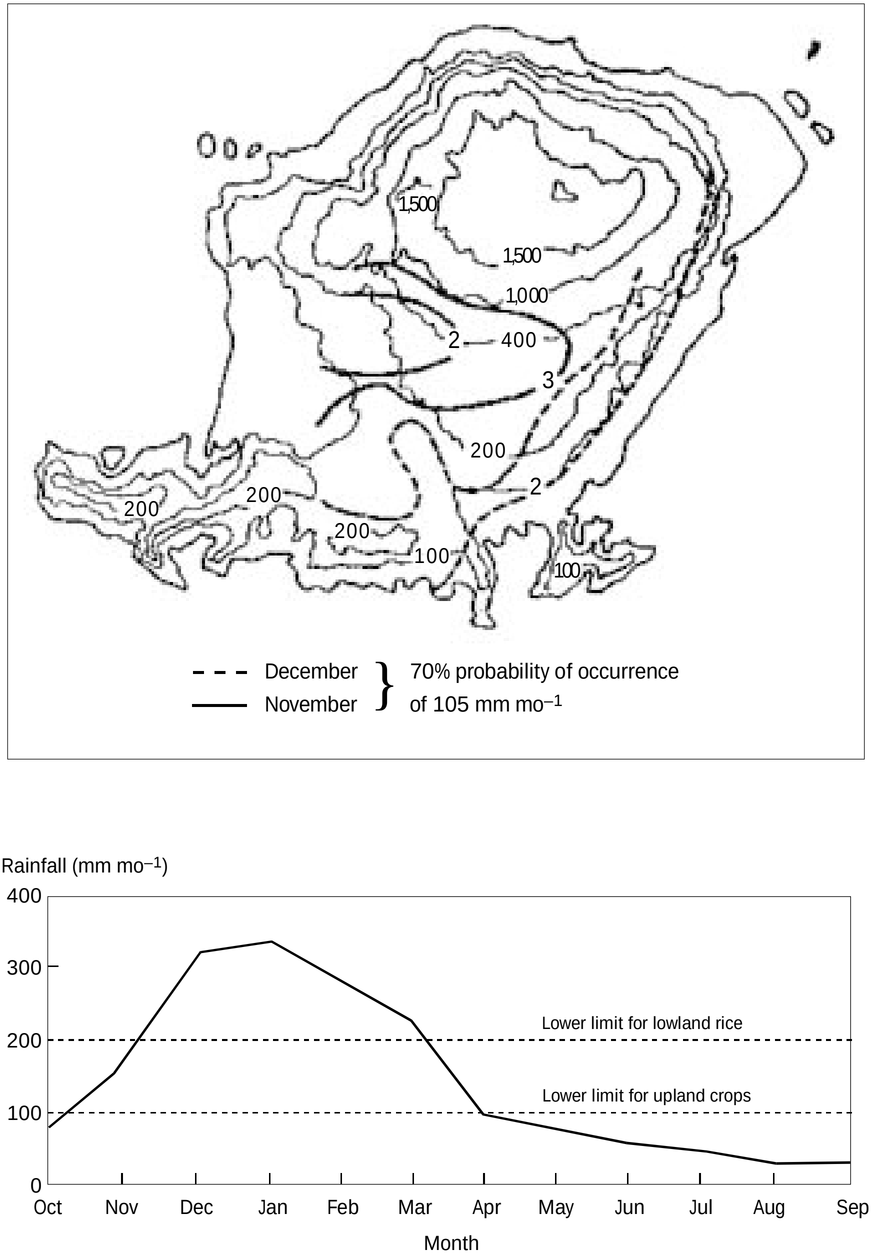

Fig. 1. Distribution of rainfall in central and southern parts of Lombok Island, Indonesia, with 70% probability of 105 mm rainfall mo^{-1} in November and December, and monthly rainfall in Sengkon where *gogorancah* rice was introduced (Sutrisno 1983 in Fagi et al 1986).

Tests of adaptability of rice varieties to *gogorancah* soil conditions conducted elsewhere in Indonesia proved that all IRRI varieties—IR5, IR26, IR32, IR36, IR38, and IR64—adapted well to the *gogorancah* system. Their adaptation was consistent in all major soil types where rice is grown (Fagi 1974, 1986, Fagi et al 1986). Among upland rice varieties, C22 was the most adapted to the *gogorancah* system. Improved lowland rice varieties planted as dry-seeded rice in the favorable rainfed lowland area produced 5.3–7.8 t ha^{-1} grain yield (14% moisture content) (Fagi 1995).

Weed competition

For *gogorancah* rice cultivation, weed infestation is a major problem. According to Giessen (1942), this problem can be minimized by starting to prepare the land at the beginning of the dry season, immediately after harvesting the wet-season rice. A secondary crop, such as mungbean, grown in the preceding dry season using residual moisture (rain) or water from a small farm reservoir, as is commonly practiced by farmers in Rembang District, Central Java, will make the weed problem in the following *gogorancah* rice less serious.

In irrigated rice areas in Indramayu District, West Java, where *gogorancah* rice is widely grown, the dominant weed species listed in decreasing order of weed population are *Cyperus iria, Ludwigia octovalvis, Fimbristylis littoralis, Echinochloa colona, E. crus-galli, Eragrostis* sp., and *Monochoria vaginalis* (Pane and Noor 1983). When *gogorancah* rice cultivation was implemented, the dominant weeds were *Cyperus difformis, F. littoralis, Paspalum distichum, E. colona,* and *Alternanthera* sp. (Pane et al 1995). Hand weeding at 15, 36, and 56 d after sowing (DAS) eliminated weeds; therefore, yield and response to nitrogen increased significantly (Table 1). There was a significant interaction between N level and time and intensity of hand weeding. Yields increased with N plus weeding but decreased with additional N if weeds were not controlled. The optimum N dose was 45 kg ha^{-1} when weeds were present but 90 kg ha^{-1} or more when weeds were controlled. Applying thiobencarb/propanil at 4.8

Table 1. Effect of time of hand weeding at various N levels on grain yield of IR36 under the *gogorancah* system, Indramayu, Indonesia, 1980-81 wet season.

N level (kg ha^{-1})	Yield[a] (t ha^{-1}) using various hand-weeding treatments					Average[b] yield (t ha^{-1})
	36 DAS	15 + 36 DAS	15 + 56 DAS	15 + 36 + 56 DAS	No weeding	
0	3.9	5.3	4.4	5.4	2.0	4.2 d
45	5.1	5.7	5.6	6.9	2.3	5.1 c
90	6.8	6.8	6.8	7.7	1.3	5.9 a
135	6.3	6.8	7.2	7.4	0.9	5.7 ab
180	5.3	7.2	6.7	7.6	0.9	5.5 bc
Average (t ha^{-1})	5.5 c	6.3 b	6.1 b	7.0 a	1.5 d	

[a]DAS = days after seeding. [b]In a column or row, means followed by common letters do not differ significantly at the 5% level by Duncan's multiple range test.
Source: Fagi et al (1986).

kg ai ha^{-1} 14 DAS was as effective as hand weeding at 21 and 42 DAS (Pane and Noor 1983).

In rainfed lowland rice area, C_4 weed species were dominant (Moody et al 1986). These weed species have a high competing ability against the rice plant. De Datta (1981) suggested that weeding be done during the first 4–6 wk of rice growth. Oxadiazon applied 1 DAS at 0.5 kg ai ha^{-1} was as effective as two to three hand weedings. Without weeding, yield loss from weed competition reached 86% (Table 2). Cisokan, an improved rice variety with fast vegetative growth, suppressed weed growth more than IR64, which has a relatively slower vegetative growth (Fig. 2). Grain yield of IR64, however, was higher than that of Cisokan.

In a press release (Suara Karya Newspaper, 18 December 1999), Sobar Praja reported that hoeing of heavy-textured soil (Vertisol) followed by pulverization of big

Table 2. Effect of weed control methods on weed weight and grain yield of *gogorancah* rice at the Jakenan Experiment Farm, Pati, Central Java, Indonesia, 1991-92 wet season.

Weed control method	Weed weight (g m^{-2})	Grain yield (t ha^{-1})[a]	Index (%)
No weeding	410 c	0.7 b	14
Hand weeding 2 times	12 a	4.9 a	100
Hand weeding 3 times	20 a	4.9 a	100
Oxadiazon (0.5 kg ai ha^{-1}, 1 d after sowing)	90 ab	5.0 a	101

[a]Means followed by a common letter do not differ significantly at the 5% level by Duncan's multiple range test.
Source: Pane et al (1995).

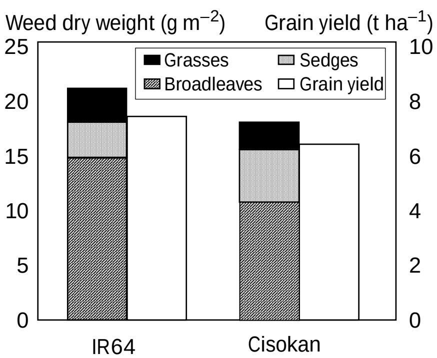

Fig. 2. Dry weed weight affected by IR64 and Cisokan rice varieties planted in the *gogorancah* system at the Jakenan Experiment Farm, Pati, Central Java, Indonesia, 1992-93 wet season (Pane et al 1995).

soil clods by pounding, with dry soil conditions for *gogorancah* rice cultivation in Punjur District, Lombok Island, West Nusatenggara, cost about \$370 ha^{-1}. Practicing no tillage and the use of herbicide (Touchdown) cost only \$30 ha^{-1}. At Jakenan Subdistrict, Pati, Central Java, the labor cost for hand weeding in *gogorancah* rice contributes to more than 50% of the total labor cost.

Nutrient management

Generally, *gogorancah* rice is grown on medium- to heavy-textured soils or on soils that have high water storage capacity. In well-established irrigated and rainfed rice areas, *gogorancah* rice plants react to fertilizer application in the same way as transplanted rice plants grown on puddled soils. Below is a summarized review of research results on fertilizer application.

- For traditional and improved rice varieties, the appropriate times of N application are 2 wk after seed germination for upland rice (aerobic soil condition) and at panicle initiation for flooded rice (anaerobic soil condition) (Giessen 1942, Fagi 1974). A split application of three equal amounts of N fertilizer in a sandy loam soil type could increase rice yield by 15% compared with two split applications (Setiobudi, this volume).
- Both Cisadane (improved rice variety) and Cempo Malam (traditional rice variety) responded more to deep-placed urea supergranules than to broadcast prilled urea at all N levels tested; the relationship between grain yields of both varieties with urea supergranule and prilled urea was linear up to 120 kg N ha^{-1} in light- to medium-textured soils (Fagi and Adiningsih 1988).
- In soils deficient in P, P fertilizer at 22.5 kg P_2O_5 or 45 kg P_2O_5 ha^{-1} applied just before sowing increased grain yields of IR5 and Dara, an improved local variety; a combination of N at 90 kg N ha^{-1} and P at 45 kg P_2O_5 ha^{-1} shortened the growing period of both varieties by 1–2 wk, reducing the exposure of rice plants to intensifying drought at later growth stages and thereby increasing grain yield (GAMA 1973).
- In K-deficient soils, C4-64 rice responded to K. Applying N and P without K did not increase grain yield because the plant was severely infected by stem rot *(Helminthosporium sigmoideum)* (Fagi 1974). The percentage of stem rot infection could reach 73% when N fertilizer (125 kg N ha^{-1}) was applied without K fertilizer to Ciliwung rice, an improved lowland variety. It was only 27% when N and K fertilizers (90 kg K_2O ha^{-1}) were applied to the rice plant together (Suparyono et al 1990). Further observation showed a similar pattern of infection for brown spot of rice *(Helminthosporium oryzae)*. When N fertilizer was applied without K fertilizer, the severity of brown spot infection was 70%, but it was only 6% when K fertilizer was added.
- A long-term study on K balances on a light-textured soil indicated that the relation between rice yield and K uptake for direct-seeded rice fell within the expected limit of maximum K dilution and maximum accumulation for well-managed irrigated rice (Wihardjaka et al 1998). Consequently, K should be applied at every planting of direct-seeded rice.

- Methane (CH_4) emission is low when N fertilizer is applied in the form of ammonium sulfate. The total amount of CH_4 emission in *gogorancah* rice was lower than that in flooded transplanted rice (Setyanto et al 1999).

Organic residues of all crops planted in rotation with *gogorancah* rice have to be returned to the soil to sustain soil fertility and rice productivity, but continuous incorporation of *Sesbania rostrata* planted in rotation with *gogorancah* rice and *walikjerami* rice (minimum tillage, transplanted rice after *gogorancah* rice) increased the population of parasitic nematode *(Meloidogyne* spp.) and consequently yield (Fagi et al 1994).

Summary and conclusions

Extreme variations in the amount and distribution of rainfall in the humid tropics are major constraints to improving and sustaining productivity of rainfed lowland rice. Under the conditions of the long wet season with high rainfall intensity over a short period on light- to medium-textured soils, rice farmers invented the *gogorancah* system (dry-seeded on nonpuddled, bunded field) to increase cropping intensity.

The g*ogorancah* system has also been used with great success in irrigated rice areas in the lowland plains, where floods commonly occur during the period from grain filling to maturing stages. The *gogorancah* system has also been successfully introduced in rainfed lowland rice areas with heavy-textured soil on Lombok Island, West Nusatenggara.

Converting the rice field from dry to wet water regimes in a *gogorancah* system subjects rice plants to two distinct soil conditions—aerobic/oxidized soil during the dry stage and anaerobic/reduced soil during the wet stage. Rice varieties adaptable to such varying conditions have to be grown. A package of technology for *gogorancah* rice has been developed. With intensive crop management, *gogorancah* rice yields comparably with transplanted rice.

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The *beushening* system of rice crop establishment in eastern India

V.S. Tomar

In India, of 42.2 million ha planted to rice, the rainfed lowland ecosystem occupies about 35%. Rice yields from this ecosystem range from 0.5 to 1.5 t ha^{-1} compared with irrigated rice yields of 3-4 t ha^{-1}. Low yields in the rainfed lowland ecosystem, specifically in eastern India, are due to drought and flood experienced in the same season, the slow spread of high-yielding varieties, poor plant populations, severe infestation of weeds including wild rice, low fertilizer-use efficiency, infertile soils, and incidence of insect pests and diseases.

Beushening is a traditional cultural practice of cross-plowing the dry-seeded (broadcast) standing crop of rice 25-35 d after seeding when 15-20 cm of rain water gets impounded in rice fields, followed by laddering and seedling redistribution. It is commonly practiced in shallow to medium submerged lowlands in eastern India. This practice loosens the soil, controls weeds, improves water-use efficiency, improves tillering and nutrient uptake, reduces insect pests, and helps redistribute seedlings. Resource-poor farmers in these areas therefore achieve moderately good production with limited inputs and less intensive labor use under conditions of uncertain rainwater and infertile soils.

An analysis of available information on different aspects of *beushening* shows that conceptually it should not be considered as a crop establishment technique only, but as a system of rainfed lowland rice cultivation. The specific biophysical and socioeconomic characteristics of eastern India and changing trends in irrigated and transplanted rice cultivation indicate that the *beushening* rice system is going to stay. Moreover, many opportunities exist to improve its productivity.

The major constraints to improving rice yields under *beushening* have been analyzed. Little information is available on different aspects of the system. In this paper, priority research issues are discussed, such as the efficient use of rainwater, the development of suitable high-yielding rice varieties, integrated plant nutrient management including green manuring, improving plant stand, supplemental weed control measures, and improved tillage/interculture implements that will help in understanding and improving rice yields.

Rainfed lowland rice occupies an important position in the agriculture of eastern India, which comprises the states of Assam, Bihar, Orissa, West Bengal, and the eastern parts of Madhya Pradesh and Uttar Pradesh. Eastern India accounts for 58% of the total rice area in the country (42.2 million ha) but less than 48% of national rice production. Yield (1.8 t ha^{-1}) is stagnant and lower than the national average (2.7 t ha^{-1}).

Hydrologically based environmental descriptions, used to discriminate rice cultural systems in eastern India, include irrigated rice and three subdivisions of rainfed rice: lowland, upland, and deepwater. About 21% of the total rice area in the region is irrigated, with an average yield of 3.2 t ha^{-1}. Rainfed lowlands account for 48% (40% shallow, 0–30-cm water depth, and 8% with medium water depth, 30–50 cm), with an average yield of 1.0 to 2.4 t ha^{-1}. Rainfed uplands constitute 16% of the total rice area, where yield is 0.6 to 1.5 t ha^{-1}. About 15% of the area is under deepwater rice, with yields of 0.9 to 2.0 t ha^{-1} (Siddiq 1998). The distribution of cropped rice area by environment is rather uniform among the six states of the region (Fig. 1).

Great improvements in rice yields in India during the mid-1960s and 70s have been made because of the Green Revolution. Advances were most pronounced in the northern and southern regions. These yield advances in irrigated areas, following the introduction of high-yielding varieties, bypassed the eastern region because the varietal technology hardly suited its highly diverse rainfed environment. The yield growth achieved in the northern and southern regions during the last three decades enabled the country to achieve and sustain self-sufficiency in rice and food. With productivity growth tapering in these regions and the area under rice shrinking nationwide, however, sustaining the present trend of productivity growth, inevitable for sustaining self-sufficiency, is not possible without increasing yield in the eastern region.

In the rainfed lowland areas of eastern India (12.8 million ha) with shallow and intermediate water, *beushening* is popular among farmers in about 50–80% of the area (Koshta et al 1991, Nayak and Lenka 1988) because they obtain stable yields with limited labor, cash, and inputs under an uncertain water supply. However, yields are low (Reddy and Panda 1985). Our understanding of the problems constraining yield and research and development efforts to remedy them are still inadequate. In this paper, the practice, its merits and disadvantages, biophysical and socioeconomic characteristics, concepts involved, and priority research issues to improve the system's productivity are discussed.

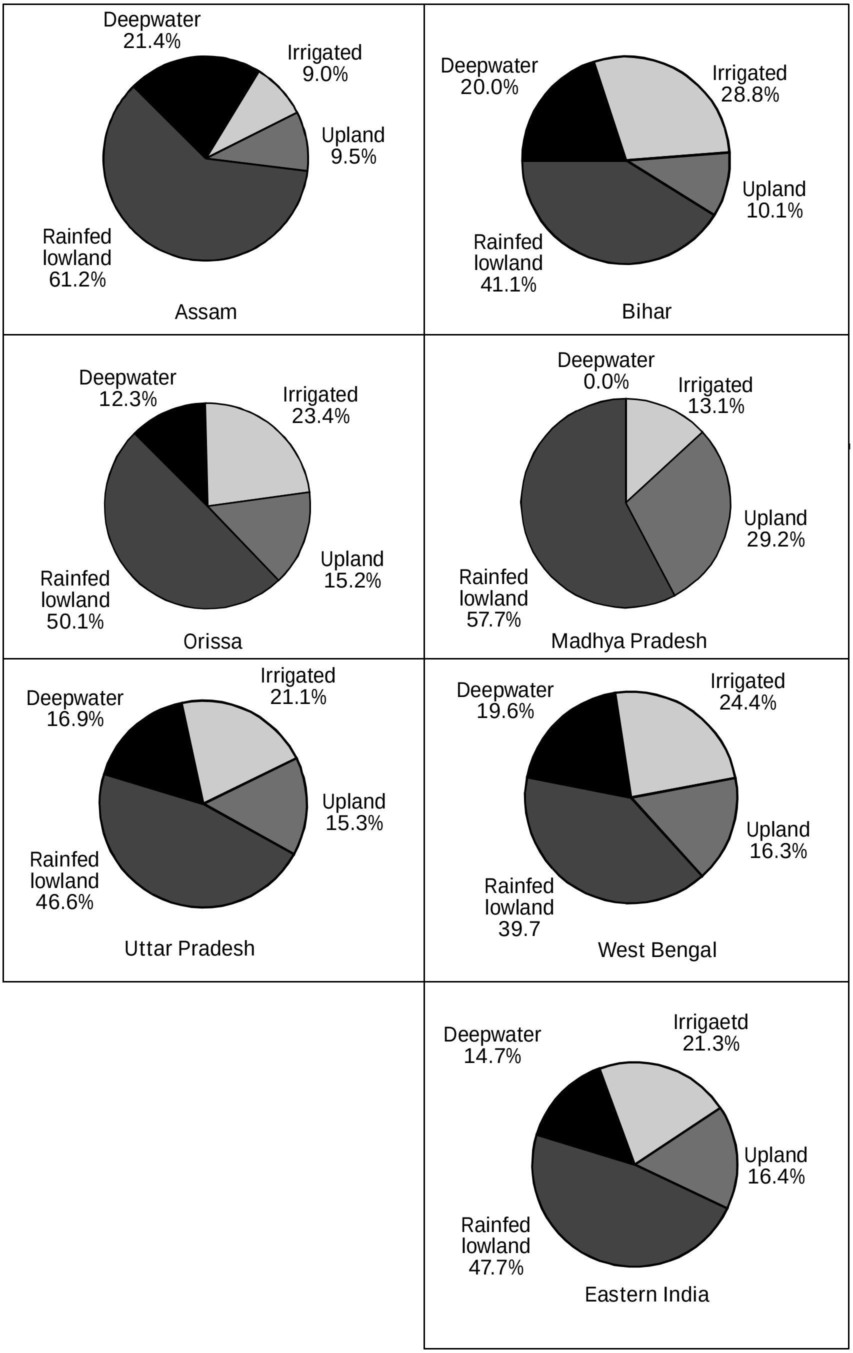

Fig. 1. Distribution of rice area (% of total rice area) by environment in different states of eastern India.

Beushening

Beushening, a traditional rice cultivation system, is common throughout the rainfed lowland region of eastern India. Locally, this practice is known as *beushen* in Orissa and Bihar, *biasi* in eastern Madhya Pradesh (Ghosh et al 1960), *lev* in eastern Uttar Pradesh (Tripathi 1979), and *baug* or *bidauni* in Bihar (Singh et al 1994). It is practiced when growing rice in risk-prone environments, which have highly variable climate and where farmers have a poor resource base. *Beushening* mainly involves two broad series of field operations: dry broadcast seeding of mostly traditional tall rice cultivars using higher seed rates than for direct seeding without *beushening* or for transplanting, and plowing the young crop crosswise 25–35 d after seeding (DAS) with a light, narrow wooden plow and laddering, when about 15–20 cm of rainwater accumulates in the field. This practice serves a triple purpose—weeding, thinning, and interculturing the crop (Ghosh et al 1960). In some cases, seedlings are also redistributed after this operation. Laddering is leveling the land after plowing with the use of a flat, heavy wooden plank. This system differs from direct-seeded and transplanted rice. In a direct-seeded system, rice is dry- or wet-seeded through broadcasting or drilling in rows, but the crop is grown without disturbing the soil and seedlings after germination. In the transplanted system, seedlings are raised in a nursery and transplanted into a separate puddled field and the crop is grown without disturbing the soil or seedlings after transplanting.

In areas where *beushening* is practiced, fields are plowed several times in winter or summer to obtain the necessary tilth. Since it is difficult to predict when the monsoon will break, rice seeds are broadcast directly in dry soil and mixed by harrowing in May-June in eastern India in anticipation of monsoon rains. In Bihar, sowing is done in the last week of May, *rohini nakshatra* (local calendar followed by farmers for cultivation practices), so that the crop matures before the late-season drought occurs in early to mid-October (*hathia nakshatra*) and in early November and thereafter. Opening up the soil in winter/summer is practiced to ensure timely sowing and the use of monsoon rains to the best advantage of the crop. Fields are bunded. Farmers use high seed rates ranging from 130 to 240 kg ha^{-1} to avoid poor plant stand (Singh et al 1994).

In some areas of eastern India, farmers let their cattle graze rice seedlings 1 wk before *beushening*. This detopping of seedlings helps improve tillering and maintain optimum plant populations, and in using crop foliage as fodder, which otherwise would be lost during plowing and laddering. Farmers apparently use grazing to minimize damage (crushing) to the upper part of the stem from plowing, laddering, and animal trampling. This is an economic way of detopping tall cultivars, thus preventing plant mortality from mud sealing. Laddering (one or two) the crosswise plowed rice fields is common in eastern India. When laddering the fields, a 15–20-kg load is put on the ladder to break the "soil slice" and loosen it without damaging the rice plants.

After these operations are done, the crop is partially weeded, seedlings are thinned wherever they are crowded, and, simultaneously, gaps in thinned-out seedlings are filled. The practice of filling gaps with seedlings from the same field is locally called *challai* in eastern Madhya Pradesh and *khelua* in Orissa (Rajput and Yadav 1993, Prusty et al 1988). However, seedlings are not redistributed in fields where plant populations are good and well distributed. In some areas, in place of partial weeding, if weeds are not well incorporated into the soil in 2–3 d of laddering, farmers repeat the laddering, but this time with a heavy load on the ladder (the plower stands on it). It is observed that two to three ladderings are sufficient to damage and incorporate weeds. Seedlings are again redistributed to fill blank patches and to thin out dense patches caused by repeated ladderings. If weeds are still present, hand weeding is done by family members after 8–10 d of laddering.

Beushening is reported to facilitate stable rice yields under low-input levels and uncertain climatic conditions. Rice cultivars mostly used by farmers are of local origin and have a long duration (150–170 d) and medium tillering capacity. These varieties can withstand drought and submergence to some extent. Yields of *beushened* rice, however, are lower than those of transplanted rice; transplanting is usually not suitable in most of these areas.

Beushening involves a series of different specific field operations throughout the crop growth period (Table 1); therefore, it should not be considered only as a crop establishment technique, but as a crop cultivation system as well. The system is based on the long experience of resource-poor farmers in risk-prone environments. If farmers' skills are improved and better rice production technologies (matching their needs) are made available, the *beushening* system can help improve rice productivity in eastern India. No alternative method is now available that can substitute for this system in the region.

Characteristics of eastern India

Eastern India is an area where *beushening*, an age-old traditional method, remains a well-adopted practice in growing rice in risk-prone environments. Resource-poor farmers use low inputs to grow rice in most of the rainfed lowland ecosystems of eastern India. A discussion on socioeconomic and biophysical characteristics of the region follows, based on Reddy and Panda (1985), Siddiq (1998), and Widawsky and O'Toole (1990).

Socioeconomic characteristics

Small and distributed landholdings. Landholdings of farmers are small and fragmented. These are generally marginal (<1.0 ha), small (1–2 ha), and medium and distributed into different land types. The average landholding size is about 1.4 ha in all eastern states except Madhya Pradesh, where it is 3.2 ha.

Poverty and illiteracy. Most rice farmers in the region are extremely poor and illiterate and have not even heard of modern rice production technologies.

Nonavailability of credit and inputs on time. Farmers are not in a position to invest in seeds, fertilizers, pesticides, implements, and other inputs. Also, they do not

Table 1. Benefits of *beushening*.

Cause	Effect	Benefit
Field preparation	Dry field preparation before the onset of monsoon	Draft power used in off-season and spread over long period Intensive labor not required Need not wait for monsoon
Seeding	Dry seeding (broadcast) Preparing nursery not needed Puddling and transplanting not required	Sowing completed on time Most efficient use of rainwater in early period Avoids early drought Saves labor in preparing nursery and transplanting No deterioration of soil physical properties compared with puddling High draft power and intensive field preparation not required
Input	Locally available inputs and family labor used	Cash not required Does not depend on credit institutions and market supply
Cross-plowing (25–35 days after sowing)	Loose and softened soil	Improves water retention, aeration, root growth, and nutrient uptake
	Uprooted weeds	Reduces weed competition
	Root disturbance	Improves tillering
	Plants knocked down	Reduces insect pests
	Plants thinned	Improves tillering and plant vigor
Laddering	Incorporated weeds	Improves soil fertility
	Weed control	Reduces weed competition
	Insects knocked down into water	Reduces insect pests
Seedling distribution	Spaced plants	Achieves better ground cover
	Plants raised out of mud	Reduces plant smothering
	Weeds removed	Reduces weed competition
Weeding and gap-filling	Weeding	Reduces weed competition
	Seedling replanting	Even ground cover

benefit from credit facilities. Farmers who can afford to invest cannot obtain a timely supply of inputs.

Subsistence farming. Most of the cereals produced are for home consumption. Monetary needs are met from selling vegetables and from off-farm employment in odd jobs during lean months. During the crop season, only family labor is engaged in farm operations. Bullocks and male buffaloes are used for draft purposes.

Physical characteristics

Land types and use patterns. Upper fields are well leveled, bunded, and adjacent to the village. These are used for cash crops. Gentle slopes of 1–2° are bunded and have a soil depth of >0.3 m. These are used for growing upland rice, wheat, black gram, pigeonpea, sorghum, and finger millets. Another category of land comprises fields in lower areas, which are bunded and retain water up to depths of 30 cm or more. These lands are used for growing lowland rice in the rainy season and wheat, gram, mustard, lentil, linseed, and other upland crops after the rainy season.

Hydrology. Although the region receives 1,200–1,800 mm average annual rainfall, approximately 55% of the area of eastern India is drought-prone, 25% is drought- and submergence-prone, 10% is submergence-prone, and 10% is favorable (Siddiq 1998). Poor drainage in lowland areas hinders the efficient use of fertilizers and other inputs.

Soils. The soils of river alluvial plains are neutral to saline, with medium fertility, and are deep. In the plateau region, most soils are acidic and shallow and have low organic matter. Soils in lower areas vary from sandy loam to clay loam to clay in texture. Lateritic soils in lowland areas are low in N, but have iron toxicity. Large areas are Zn deficient (Reddy and Panda 1985). The long period of rice cropping without adequate fertilizers has depleted most rice soils in the region of important macro- and micronutrients. Virtually every rice field in the region responds favorably to fertilizer application. The low nutrient status of soils is one of the major constraints to rice production.

Biological environment

Weeds. Weed populations and growth are vigorous. Weeds are the second most important constraint to rice yields after drought and submergence.

Insect pests and diseases. High humidity and high temperature in rainfed lowlands facilitate the buildup of pest populations. Among insect pests, ant, yellow stem borer, gall midge, green leafhopper, leaffolder, brown planthopper, hispa, and nematodes cause considerable damage to rice. Among diseases, bacterial leaf blight is endemic in the region and leaf blast, sheath blight, and sheath rot also cause damage to rice.

Crops. Rice is the main crop in the rainy season, followed by wheat, mustard, chickpea, pea, vegetables, or linseed after the rainy season. Traditional tall rice varieties are susceptible to lodging.

Advantages of *beushening*

Lower labor requirement and labor demand spread over time

In *beushened* rice, labor saving is primarily in nursery growing, land preparation, transplanting, and weeding operations. Singh et al (1994) reported that the labor requirement in *beushening* is only 62% of that in transplanted cultivation. Also, labor demand is spread over a longer time (Fig. 2) because the operations, especially

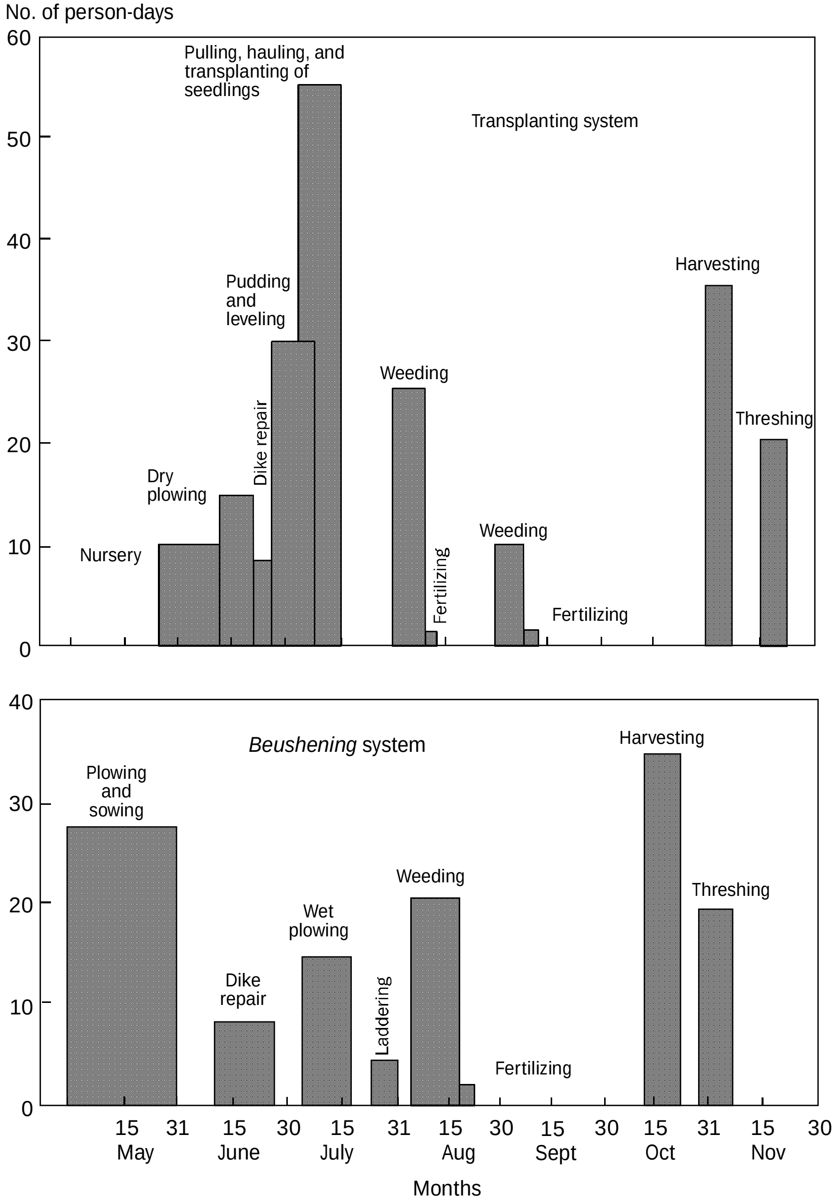

Fig. 2. Distribution of labor input use in *beushening* and transplanting system (after Singh et al 1994).

land preparation, wet plowing, and hand weeding, are done over a longer period. Land preparation in *beushening* is done in as much as 3–4 mo, and generally in the off-season before the start of the rainy season. In the transplanting system, this operation has to be completed in 3–4 wk after the onset of monsoon to ensure timely transplanting. Also, transplanting requires a large amount of labor and in a short period, such as a few days or a week at most. More than 50% of the total labor requirement in the transplanting system is for plowing, puddling, and leveling and pulling, hauling, and transplanting of seedlings in about a month, whereas in *beushening* it is not more than 25% in any month. Similarly, weeding is a single operation in *beushening*, spread over a longer duration; whereas, in the transplanting system, it is usually done twice and over a shorter duration. Because of the spread of the labor demand over a longer period in the crop season, most *beushening* operations are done by family labor.

Less animal power

The *beushening* system requires less animal power than the transplanting system. Animal power is required for only 42 d ha^{-1} in the *beushening* system compared with 50 d ha^{-1} in the transplanting system (Singh et al 1994). Also, in *beushening*, it is spread over 4–5 mo compared with only 1 mo in the transplanting system.

Low fertilizer requirement

In *beushening*, cultivators use traditional tall varieties that do not respond economically to higher doses of chemical fertilizers. High-yielding varieties that respond favorably to higher levels of NPK fertilizers are not well suited for *beushening*. Some farmers use organic or green manure for which cash is not required.

Higher water-use efficiency

Eastern India receives a high annual rainfall, averaging 1,200 to 1,800 mm, of which 80% is concentrated during the peak monsoon season (Jun-Oct). Even then, the rainfed lowland crop suffers because of poor rainwater management practices. The *beushening* system, which requires no water for nursery raising, puddling, and transplanting, uses rainwater more efficiently because the beneficial effects of both dry direct seeding (early crop establishment and efficient use of early monsoon rains) and puddling (wet plowing and laddering reduce water percolation losses from fields) (Tomar 1997) are incorporated in the practice. The *beushened* rice thus helps meet the crop water requirement at different growth stages (Tomar and O'Toole 1980), avoids later stage drought, and uses rainwater more efficiently.

Less cash inputs

In *beushening*, farmers do not buy expensive seed of high-yielding varieties because they use their own seed of traditional tall varieties. Most field operations are performed by family labor and therefore rarely use hired labor. Farmers also spend very little on fertilizers, pesticides, herbicides, and other inputs.

Nursery raising and puddling not required

In *beushened* rice, seeds are broadcast directly in dry soil; therefore, nursery raising and puddling are not required. Because of the shortage of water and the problem of stray animals during summer months, it is difficult to raise seedlings in a nursery, and raising crops in a nursery is very expensive. Thus, not having a nursery saves on the labor cost substantially.

For puddling, farmers may have to wait to accumulate enough rainwater in the field, which, even in normal years, is possible only in late July to early August. Thus, in transplanting, crop establishment is delayed and the crop suffers from drought in mid-October, nearly at the flowering stage, which is avoided in *beushened* fields.

Reduced weed problems

Fields for *beushening* are repeatedly plowed during winter/summer and therefore have less weed problems. The remaining weeds are buried in the mud during wet plowing and laddering done 25–35 d after germination. This process further helps check the carryover of weed seeds to the following year, specifically of wild rice. If weeds are still present in the field after laddering, partial weeding can be done using family labor. Chandra (1999), in a no-hand-weeding field study, reported weed weight at the time of harvesting the rice crop of 434 g m^{-2} in *unbeushened* rice compared with 124 g m^{-2} in *beushened* rice (Table 2). *Beushening* controls up to 70% of weeds.

Reduced insect and disease problems

Beushened fields have few problems with insects and diseases. Rodents are reduced because their burrows are destroyed by plowing in summer. During plowing and laddering, insects are knocked down into the water with seedlings, resulting in reduced insect pest damage. This practice helps minimize infestation of pests such as gall midge (Singh et al 1994).

Table 2. Effect of *beushening* on dry weight of weeds at harvest.

Treatment	Variety	Dry weight (g m^{-2})			Mean
		LS[a]	BS	NBS	
Hand-weeding	T 141	85	71	95	84
	Moti	99	69	106	91
	Padmini	86	46	76	69
	Mean	90	62	92	
No hand-weeding	T 141	232	171	760	388
	Moti	215	103	295	204
	Padmini	136	100	249	162
	Mean	194	124	434	

[a]LS = line sowing; BS = *beushening* (0–40-cm water depth); NBS = *unbeushened*.
Source: Chandra (1999).

Suitability to drought- and submergence-prone areas

Rainfed lowlands in eastern India are characterized by moderate to severe drought during the early and mid growing season and by occasional submergence/flooding of variable duration and depth (Singh 1996). Transplanted or direct-seeded rice cultivation in such areas is not economically feasible because of erratic rainfall and undulating topography, which causes the crop to suffer from drought or floods or both, sometimes in the same season.

Stable yields

Although yields of *beushened* rice are low, they are more stable than those of transplanted or direct-seeded rice. Even in years of low rainfall at the beginning of the season, when transplanted rice is not possible, farmers harvest a successful *beushened* crop. The rainfall pattern in eastern India, in years of delayed early monsoon, has been characterized by continuous rains until early November and hence no drought risk in mid-October (Singh 1996). Therefore, even in cases of total crop failure caused by severe and extended drought at the beginning of the season (mid-June to mid-July), a *beushened* crop is feasible from a second sowing in mid-July, with only additional seed cost and family labor. During years when continuous rain occurs in early months, *beushened* rice is possible, but not transplanted rice because of floods. Also, in years of heavy flooding at the time of wet plowing and laddering, the crop can continue as a direct-seeded crop without these operations (Singh et al 1994). Stirring the soil and seedlings 25–35 DAS also improves tillering and nutrient uptake and causes better root development. These processes help stabilize rice yields (Ghosh et al 1960).

Ease and timely establishment of a nonrice crop after rice

In a review of soil physical limitations for rainfed lowland rice, Tomar (1997) reported that continuous puddling for several years reduces rice yields and creates difficulty in establishing nonrice crops after rice because of the deterioration of soil physical properties and subsoil compaction. Transplanted rice is also harvested 2–3 wk later than *beushened* rice. Furthermore, land preparation after transplanted rice is difficult and delays sowing of a nonrice crop (Tiwari et al 1999). The subsequent crop in transplanted rice fields yields lower than in direct-sown fields (Table 3). Moreover,

Table 3. Effect of methods of rice cultivation and postrice tillage on wheat yield (mean data for 1994-95 and 1995-96).

Treatment	Wheat yield (t ha^{-1})			Mean
	Direct-seeded	Lehi	Transplanted	
No tillage	4.5	4.0	4.0	4.2
Conventional tillage	3.7	3.5	3.1	3.4
Deep tillage	3.4	3.3	2.9	3.2
Mean	3.9	3.6	3.3	

Source: Tiwari et al (1999).

in rainfed areas, the subsequent crop suffers from soil moisture depletion even at early growth stages, resulting in poor crop establishment. Such problems, however, are not encountered in *beushened* fields. Moreover, crops grown after rice can use residual soil moisture more efficiently.

Disadvantages of *beushening*

Low plant stand

In *beushening*, insufficient rain after sowing results in poor germination and low plant stand. Rain must be adequate to promote fast seed emergence, better plant stand, and high yield. *Beushening* also results in some damage to rice seedlings and their uneven distribution (Chandrakar and Chandrawanshi 1985, Nayak and Lenka 1989). Therefore, farmers use higher seed rates, ranging from 130 to 240 kg ha^{-1} (Singh et al 1994), to compensate. Further, flash floods just after *beushening* usually increase plant mortality.

Poor weed control

Weeds are the second most important constraint to rice production after drought/submergence in eastern India (Widawsky and O'Toole 1990). They depress yield considerably in direct dry-seeded lowlands. Infestation of *balunga* or *karga* (wild rice) is a serious problem in eastern Madhya Pradesh. The effectiveness of traditional cultural operations such as *beushening*, which helps minimize weed infestation, depends on an active monsoon in the early stages of crop growth. When *beushening* is delayed because of rain, weeds grow well and use up most nutrients for the rice crop and also suppress tillering.

Weed control has been reported as a major advantage of *beushening* (Pillai 1958, Ghosh et al 1960, Maurya 1989, Singh et al 1994). However, the type of weed flora in this ecosystem varies highly. At the early stage, the crop suffers from heavy weed infestation and, if monsoon is delayed, losses from weeds increase. *Beushening* is highly effective in controlling monocot weeds such as *Echinochloa colona* and *E. crus-galli*, which are widespread. If partial weeding after *beushening* is not done, many weeds remain in *beushened* fields.

Lack of high-yielding varieties

Semidwarf short-duration cultivars are reportedly unsuitable for *beushening* as their grain yield decreases considerably because of stem breakage during wet plowing and laddering (Singh et al 1994). *Beushening* is not good for all rice varieties in the lowland ecosystem irrespective of stature, quality, and duration. Chandra (1999) reported that, among three medium-duration rice cultivars differing in stature and quality, *beushening* was beneficial for semitall (115 cm) variety Moti, which produced 38% extra yield compared with an *unbeushened* crop. A superfine rice variety, Padmini, 130 cm tall, produced 35% higher grain yield when sowed in lines compared with *beushening* under weed-free treatments (Table 4). This reduction in grain yield of Padmini under *beushening* has been reported to be caused by poor culm

Table 4. Grain yield of rice varieties as influenced by *beushening.*

Treatment	Variety	Grain yield of rice (t ha^{-1}) LS[a]	BS	NBS	Mean
Hand-weeding (weed-free)	T 141	2.3	2.5	2.7	2.6
	Moti	3.7	3.9	3.6	3.7
	Padmini	3.1	2.3	1.9	2.5
	Mean	3.0	2.9	2.8	2.9
No hand-weeding (weedy control)	T 141	2.2	2.1	1.4	1.9
	Moti	1.7	2.4	0.5	1.5
	Padmini	1.1	1.2	0.4	0.9
	Mean	1.7	1.9	0.8	1.5

[a]LS = line sowing; BS = *beushening* (0–40-cm water depth); NBS = *unbeushened*.
Source: Chandra (1999).

thickness, which might not help plants to stand, resulting in lodging. The number of ear-bearing tillers has been reported to be only 145 m^{-2} under a *beushened* crop compared with 226 m^{-2} under a line-sowed weed-free situation.

Lodging
Most farmers in eastern India grow traditional tall-statured rice varieties that are susceptible to lodging. Available information indicates that, depending on lodging stage, losses could be from 30% to 80% (Widawsky and O'Toole 1990).

Poor use of applied nutrients
Untimely and uncertain rainfall, causing moisture stress or flooding in rainfed rice, results in poor use of applied nutrients. In a 2-y experiment, Sheela and Alexander (1995) observed that, during 1991 when rain was well distributed, medium-duration variety Jaya performed best. However, in 1992, when the crop experienced drought at the flowering and milk stages, short-duration Tulasi escaped drought, whereas Jaya suffered a yield reduction even under well-fertilized conditions.

Lower crop yield
Lower yields of rice in the *beushening* system are due to reduced plant stand, poor weed control, less spread of high-yielding varieties, lodging, low fertilizer use and lower fertilizer-use efficiency, almost negligible use of plant protection measures, and drought and flood (Prusty et al 1988, Nayak and Lenka 1988, 1989, Singh et al 1994, Chandra 1999).

Priority research issues

Out of 40 million ha worldwide of rainfed lowland area, nearly 32% is in eastern India where *beushening* is popular. This region not only has low and variable yields but also has a higher incidence of poverty. According to Pandey (1997), improvement in rice productivity could be the key to income enhancement and poverty reduction in rice production systems where population density is high and income is low.

Among the top 10 abiotic and biotic constraints that cause a yield reduction in rainfed lowland environments in eastern India, anthesis drought is the most important, followed by weeds, submergence, seedling drought, lodging, blast, yellow stem borer, Zn deficiency, bacterial blight, and vegetative drought (Widawsky and O'Toole 1990). Moreover, current trends of reduced profitability of irrigated rice production systems (Pandey 1997) and switching from transplanting to direct dry-seeded rice because of erratic rainfall (Prasad et al 1994) indicate that the *beushening* system of direct dry-seeded rainfed rice is inevitable for this region. Therefore, concentrated efforts by scientists are needed to increase the system's productivity. Some of the priority research issues are discussed here.

Moisture availability and water balance

The rice crop in the region experiences both drought and submergence in the same season. Fields that accumulate less than 5 cm or more than 30 cm water depth generally are not preferred for *beushened* rice. Water depths of 10–25 cm are considered normal for wet plowing and 5–10 cm for laddering; hence, farmers select such fields for *beushened* rice based on past experiences and prepare/repair bunds with provision for drainage to maintain the desired water depth.

The scientific analysis of moisture availability and water balance for a given location may help farmers in preparing their crop calendar and improving rice productivity and cropping intensity. An analysis by Singh (1996) showed that the duration of moist I, humid, and moist II periods varied considerably in six states of eastern India (Table 5). The water balance study for a rice crop at Tilda, Madhya Pradesh (Fig. 3), shows specific periods of water deficit and surplus, moisture use, and recharge pattern. Up to the end of July, rainfall exceeded meeting potential evapotranspiration (PET) and recharged the soil moisture. From the last week of September (39th standard week), however, water deficit conditions prevailed. Thus, long-duration

Table 5. Range of moisture availability period in different states of eastern India.

State	Range of moisture availability period (d)[a]		
	Moist I	Humid	Moist II
Uttar Pradesh	12–18	81–123	17–22
Madhya Pradesh	10–16	103–147	12–21
Bihar	12–18	95–139	17–22
Orissa	12–14	131–165	15–18
West Bengal	16–28	130–187	13–22
Assam	21–33	191–205	11–22

[a]Moist I refers to moisture availability period when rainfall is less than PET but greater than half of PET at the beginning of the rainy season or Moist II at the end of the rainy season. When rainfall exceeds PET, the period is called humid.
Source: Singh (1996).

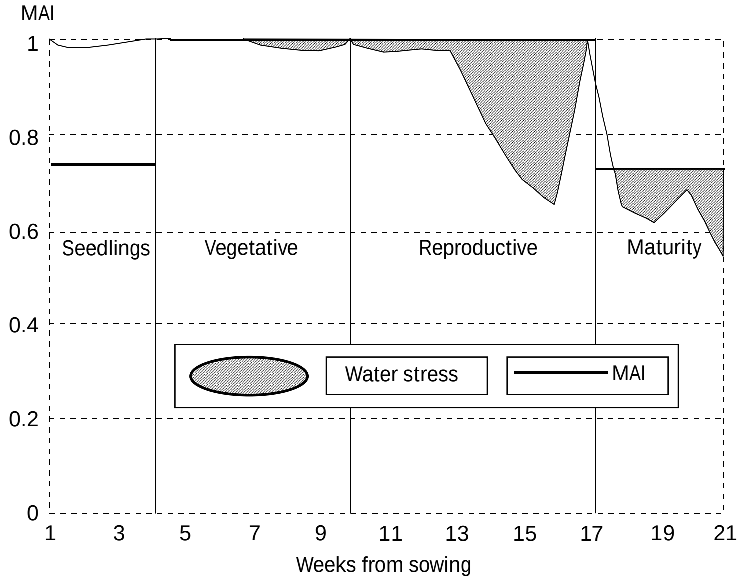

Fig. 3. Weekly pattern of moisture availability index (MAI) during the growth period of long-duration rice genotypes (after Singh et al 1999).

rice varieties suffer more from water shortage during the reproductive and maturity stages than short-medium-duration ones. Such an analysis is important in location-specific planning for crop production strategies including allocation of resources and selection of cultivars for critical operations.

Most of the precipitation received as high-intensity storms of very short duration is prone to runoff, seepage, and percolation losses, causing water stress to rainfed rice, with devastating effects, especially during extended dry spells. In view of this and limitations to expanding conventional irrigation in eastern India, the possibilities of improving the water supply to rainfed rice lands through rainwater storage systems need to be explored (Bortrall and John 1991, Dhawan 1989, Pal et al 1994). This may involve a renewed emphasis on community participation in the use of tanks, stop dams, and diversion dams for the storage and efficient use of rainwater. Moreover, on-farm reservoirs owned by individual farmers may help reduce crop losses from drought and submergence.

Integrated plant nutrient management including green manuring

Soils in eastern India vary from sandy loam to clay loam to clay, shallow to deep highly fertile alluvial plains to very low fertility red lateritic soils, with iron toxicity to deficiency of zinc, sulfur, and iron, and experience drought and submerged conditions in the same season. Presently, farmers use little or no fertilizer and, if they do, it is only nitrogen or sometimes diammonium phosphate after *beushening* and hand-weeding operations. They rarely go for a balanced use of fertilizers.

Farmers believe that traditional cultivars suitable for *beushening* require lower fertilizer inputs and, even at half-fertilizer rates, that they yield on a par with the transplanting system. Information on optimum doses of NPK and micronutrients, such as zinc for cultivars suitable to *beushening*, is lacking.

Green manuring of *beushened* rice with leguminous crops is reported to save about 40–60 kg N ha^{-1} and increase grain yield significantly over *beushening* alone (Ghosh et al 1960, Manna et al 1988, Chandra 1999). Work done at Cuttack as early as in 1953-56 (Ghosh et al 1960) revealed that growing *dhaincha* (*Sesbania aculata* or *S. rostrata*) mixed with rice and wet plowing it under at the time of *beushening* increased rice yield by 366 kg ha^{-1} (Table 6). Similarly, according to Manna et al (1988), the grain yield of broadcast-sown rice, along with *dhaincha* and incorporating the latter after 40 d through *beushening*, was comparable with applying 40 kg N fertilizer ha^{-1}. Green manuring can sustain up to 50% of chemical N fertilizer when the N requirement of rice is up to 90 kg ha^{-1} under shallow lowland or irrigated conditions. The N requirement (40 kg ha^{-1}) of direct-sown rice under intermediate deepwater lowland can be fully met by incorporating *dhaincha* while *beushening* (Table 7). About 70–90% of N in *Sesbania* sp. is fixed in 40–55 d. A suitable green-manuring species that can fix more N_2 in a shorter period (30–35 d) for *beushening* should be found.

Interest has increased in the use of blue-green algae (BGA) and *Azolla* as a supplementary source of N for rice. Chandrakar et al (1983) reported that, in a study at several locations, BGA increased rice yields up to 19% and also had some residual effect on the succeeding chickpea. Mahapatra et al (1987) reported that rice yields with *Azolla* inoculation and 30 kg N ha^{-1} were the same as with 90 kg N ha^{-1} applied as prilled urea. In a study at Raipur, Koshta et al (1991) showed that neem cake-coated urea can improve N-use efficiency significantly over prilled urea in rice. For the economically poor but bio-organic resource-rich farmers of eastern India, the integrated plant nutrient supply system, which involves meeting part of crop nutrient needs through organic manure, crop residue, green manure, and biofertilizer, requires the attention of rice scientists. Such cheaper technology will help provide all the required nutrients in a balanced amount as well as maintain and improve physical and biological properties of soils in *beushened* rice.

Table 6. Effect of growing *dhaincha* (green manure) with rice on paddy yield (1953-56).

Treatment	Paddy yield ($t\ ha^{-1}$)
Paddy	2.1
Paddy + *dhaincha*	2.5
Paddy + *dhaincha* + 20 kg N	2.6
Paddy + *dhaincha* + 50 kg P_2O_5	2.5
Paddy + *dhaincha* + 20 kg N + 50 kg P_2O_5	2.6
CD ($P = 0.05$)	0.26

Source: Ghosh et al (1960).

Table 7. Effect of green manuring and *beushening* on lowland rice yield.

Treatment	Paddy yield (t ha^{-1})	
	1985	1986
T_1 No *beushening*	3.5	2.2
T_2 T_1 + 40 kg N ha^{-1} after flowering	3.8	2.4
T_3 T_1 + 40 kg N ha^{-1} at 40 DAS[a]	4.0	2.5
T_4 *Beushening* alone at 40 DAS	4.3	2.7
T_5 T_4 + 40 kg N ha^{-1} after flowering	4.4	2.7
T_6 T_4 + 40 kg N ha^{-1} at *beushening*	4.9	2.7
T_7 T_4 + green manuring	4.8	3.0
T_8 T_5 + green manuring	4.7	2.9
T_9 T_6 + green manuring	4.5	2.8
CD (P = 0.05)	0.19	0.10

[a]DAS = days after sowing.
Source: Manna et al (1988).

Suitability of improved rice cultivars

Under *beushening*, farmers grow traditional tall varieties because they adapt well to this practice under adverse conditions such as waterlogging, drought, and low soil fertility and provide rice straw, which is valuable in rural areas. These varieties, however, are low yielders because of their susceptibility to lodging, insect pests, and diseases and low response to fertilizers. Suitability of cultivars is specific to the rice cultivation systems of transplanting or *beushening* (Singh et al 1994). However, for traditional cultivars, transplanting has no distinct advantage over *beushening*.

Results of front-line trials conducted in eastern India (Singh 1991) have shown that the adoption of appropriate high-yielding varieties and use of high-quality seed and fertilizers could increase yields by 40–60% over local varieties cultivated under conditions of poor crop management (Table 8). However, the performance of these varieties under the *beushening* system needs to be evaluated.

To increase the productivity of *beushening*, improved varieties with higher yield potential and greater yield stability that can use stored water from deeper layers during drought (Tomar and O'Toole 1979) are required. Farmers' preference for photoperiod-sensitive cultivars of long duration (120–150-d maturity) should also be considered. Therefore, plant architecture must be modified to improve the harvest index, and genes for biotic and abiotic stress tolerance must be incorporated to increase yield stability.

Gap-filling and weed control supplementary practices

Beushening followed by gap-filling (improved *beushening*) has been reported to result in significantly higher yields over *beushening* alone. Chandra (1999) at the Cuttack Rice Research Institute (CRRI), Cuttack, observed that *beushening* followed by gap-filling gave a maximum yield of 3.5 t ha^{-1}, which was 13% more than the yield of *beushened* rice. *Biasi*, a practice like *beushening* in eastern Madhya Pradesh,

Table 8. Grain yield of improved and local (L) rice varieties in rainfed lowlands in eastern India.

Site/state	Crop establishment	Water regime (cm)	Variety	Grain yield (t ha^{-1})	Increase over local variety (%)
Masodha, Uttar Pradesh	Transplanted	15–20	NC 492	2.0	33
			Madhukar (L)	1.5	–
Raipur, Madhya Pradesh	Direct-seeded	0–30	R 320-300	4.1	20
			Safari (L)	3.4	–
Patna, Bihar	Direct-seeded	0–30	Radha	3.9	92
			Local	1.8	–
Titabar, Assam	Transplanted	0–30	TTB 101-7	4.8	29
			Safari 17 (1)	3.4	–
		30–50	IR3459-8-1-2	5.5	61
			Manohar Sati (2)	2.7	–
Chinsura, West Bengal	Transplanted	0–30	IR42	4.4	62
			Jhingasali(2)	2.7	–
		30–50	NC 492	3.5	40
			Soukaluna (L)	2.5	–
Kendrapara, Orissa	Transplanted	0–30	OR 609-15	4.7	30
			Mochi Banki (L)	3.6	–
		30–50	NC 492	4.8	55
			Athorgadia (2)	3.1	–

Source: Singh (1991).

followed by gap-filling also gave a yield as high as in the transplanting system (Rajput and Yadav 1993). Moreover, Koshta et al (1991) recommended that, for higher yields, extra seedlings be arranged for gap-filling by either growing at three times the seed rate in 1/20th of the field area or raising an additional nursery of 2–5 kg ha^{-1} in addition to the 100 kg ha^{-1} used for sowing in the *biasi* method. This technology still requires refining to ensure optimum populations for different cultivars.

Excessive weed growth is the first major constraint to dry-seeded rice in rainfed areas. Under timely *beushening*, more than 70% of weeds are controlled (Chandra 1999, Singh et al 1994, Saha et al 1999, Prusty et al 1988). Even the interculture operation done after 25–30 d of broadcasting sprouted rice seeds in puddled soils, called *holod* in Himachal Pradesh, has been reported to reduce weeds significantly and increase mean grain yield by 19.3% over non-*holod* (Angiras and Rana 1998). Evaluation of weed control methods in field trials at Kanke, Bihar, revealed that, in direct-seeded lowland rice, *beushening* at 25 DAS + hand weeding at 40 DAS was next best to a weed-free treatment and comparable with chemical control at 20 DAS + hand weeding at 40 DAS (Saha et al 1999). Research on effective weed control measures in the early stage and after *beushening*, along with improving seedling populations in *beushened* rice, needs attention.

Improving germination and plant stand

Because of poor plant stand in direct dry-seeded broadcast rice, farmers use a high seed rate. Various practices, such as line sowing (Koshta et al 1991), seed priming with potassium chloride, application of higher doses of potassium to provide early vigor (Thakuria and Sarma 1995), and timely sowing, that is, sowing a week before the onset of monsoon (Kathiresan et al 1997), may improve germination and plant stand. Well-planned research is required on this aspect under the *beushening* system.

Improved tillage and interculture implements

Research is needed to expand knowledge of tillage and interculture (*beushening*) principles by studying the effects of alternative tillage/interculture implements and soil manipulation on changes in soil environment, incorporation of weeds/green manure in soil, and plant growth. Local farm implements are now used for tillage/ interculture operations with draft animals. Along with looking into improvements in existing farm implements, the possibility of using power implements should be assessed because, with the changing agricultural production scenario, the use of draft animals in agriculture is decreasing significantly.

Resource use, management decisions, and the productivity of rainfed farms totally depend on rainfall and are constrained by both unfavorable biophysical and economic conditions. For this resource-poor region of India, *beushening* still appears to be the most suitable crop cultivation system because it has the advantages of both direct-seeded and transplanted rice, high water-use efficiency, less labor intensity, and less expense. I hope that rice scientists will be able to generate new technologies to improve the existing age-old traditional system of rice cultivation to make it more profitable.

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Environmental conditions as determinants of direct seeding techniques in different ecosystems in the Mekong Delta of Vietnam

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Direct seeding, a common traditional cultural practice for floating rice used by Mekong Delta farmers for hundreds of years, became more widespread after the introduction of modern rice varieties IR5 and IR8 in 1968. The area under direct seeding of modern rice in the Mekong Delta has increased markedly during the last three decades because of crop intensification as well as labor shortage and other economic factors. Farmers direct-seed their rice in both irrigated and rainfed ecosystems and under diverse environmental conditions. Four typical direct-seeding techniques of rice were observed: zero-tillage seeding, water seeding, dry seeding, and wet seeding. The productivity of each type of direct-seeding method and the corresponding farmer income are discussed. Most common modern rice varieties with short growth duration (90–105 d) can be used successfully in the four seeding methods. Farmers can enhance rice land productivity and labor efficiency by selecting an appropriate direct-seeding method considering soil and hydrologic conditions of their field, availability of appropriate land preparation equipment, and irrigation-drainage systems in the locality.

One hundred years ago, Mekong Delta farmers used direct seeding for their floating rice. Since the early 1980s, direct seeding of rice has quickly replaced transplanting because of increased cropping intensification, higher costs for transplanting, lack of farm labor, and the availability of short-duration rice varieties. This occurred in all irrigated and rainfed ecosystems under diverse environmental conditions. Farmers in the Mekong Delta use these four typical direct-seeding techniques: (1) zero-tillage seeding (*sa chay*), (2) water seeding (*sa ngam*), (3) dry seeding (*sa kho*), and (4) wet seeding, an ordinary direct-seeding technique (*sa mong*).

This paper describes various direct-seeding practices in different rice ecosystems in the Mekong Delta and analyzes farmers' choices of these practices in relation to environmental conditions and production systems.

Major agroecological zones using modern rice cultivation in the Mekong Delta

The Mekong River Delta, covering approximately 4 million ha, can be divided into seven major agroecological zones (Fig. 1). Among these are five zones predominantly under modern rice cultivation.

Fresh-water alluvium zone

The fresh-water alluvium zone covers 900,000 ha. The zone is mainly located along the banks of the Tien and Hau rivers. Most soils are alluvial and rich in humus and total N. In some places, the soil is slightly or moderately acid. The annual inundation

Fig. 1. Agroecological zones of the Mekong Delta, Vietnam. (Source: Xuan and Matsui 1998.)

occurs earlier in the northern parts of the delta (from August to October). The southern part is shallowly inundated at a depth of 0.5–1.0 m (Fig. 2). The inundation period lasts 2 to 3 mo, from September to November. Areas with an irrigation system and shallow inundation have three rice crops a year: winter-spring, spring-summer (or early summer-autumn), and late summer-autumn (Fig. 3).

Plain of Reeds

The Plain of Reeds located in the northern part of the delta consists of the lowest areas of Dong Thap and Long An provinces, with an area of about 500,000 ha. The soil consists mainly of acid sulfate soils. Inundation occurs from August to November with a depth of 1.5–3.0 m. Part of the zone that has fresh-water irrigation is now under

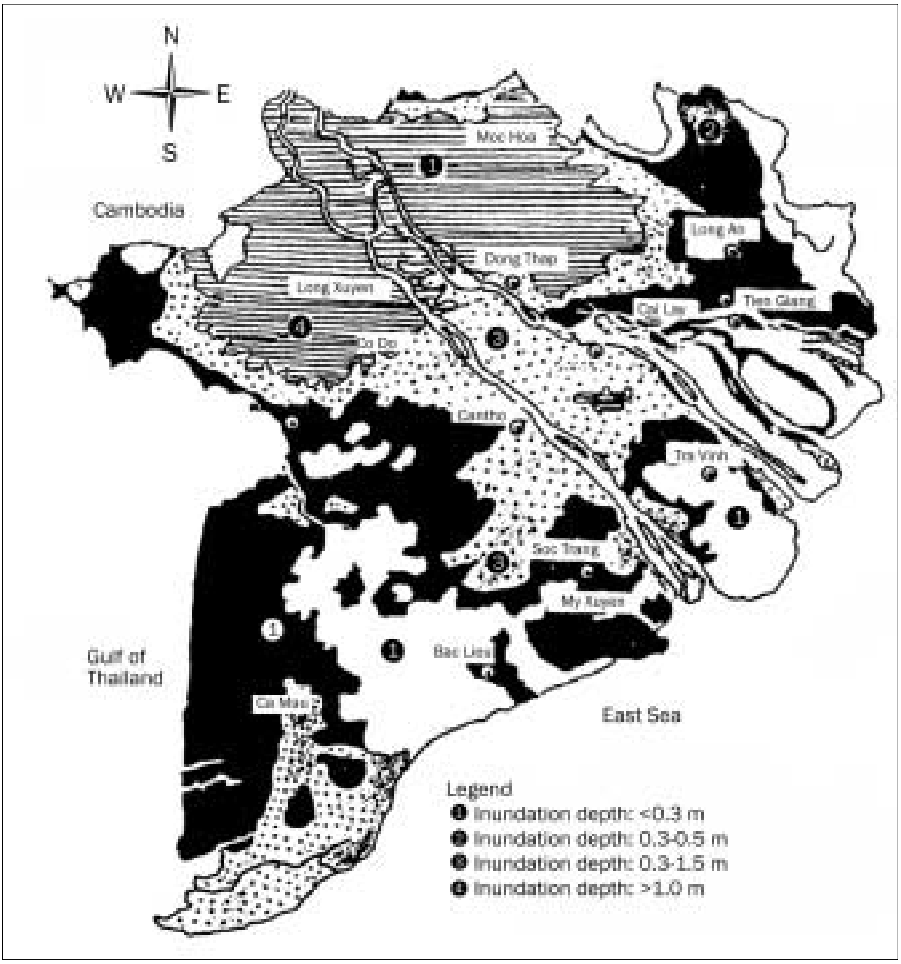

Fig. 2. Inundation of the Mekong Delta, Vietnam. (Source: Xuan and Matsui 1998.)

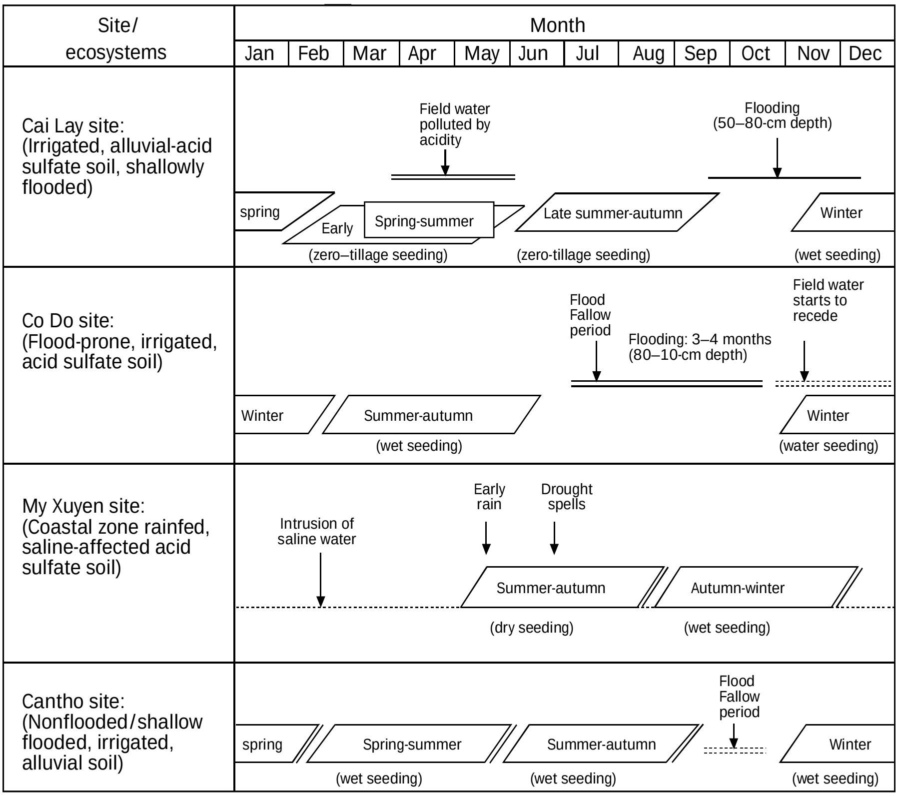

Fig. 3. Rice cropping calendar at different sites representing the various ecosystems in the Mekong Delta of Vietnam.

rice cultivation. Two rice crops, winter-spring and summer-autumn, can be grown on these soils each year.

Long Xuyen–Ha Tien quadrangle

The Long Xuyen–Ha Tien quadrangle is located in the northwestern part of the delta. This zone covers about 400,000 ha and is also dominated by acid sulfate soils. The soil is rich in humus but low in phosphorus. In addition, Al and Fe toxicities limit yield. The area is inundated for 3–4 mo a year with a depth of more than 1 m. In many places where there is fresh-water irrigation, two rice crops can be grown per year. In other places, acid soils sustain only *Melaleuca* and *Eucalyptus* trees, pineapple, and other crops.

Trans-Bassac Depression

This zone covers 600,000 ha and includes areas of An Giang, Kien Giang, and Cantho provinces. Its soils are not very fertile and are slightly or moderately acid sulfate. The inundation period lasts 3 to 4 mo with a depth of 0.5–1.0 m (Fig. 2). In the past, most of the area was used for floating rice or deepwater rice (one crop per year). Now, two rice crops, winter-spring and summer-autumn, are planted each year. Water direct seeding is practiced for the winter-spring crop in some places.

Coastal zone

The coastal zone stretches from the eastern parts of Tien Giang, Ben Tre, and Tra Vinh to Soc Trang and Bac Lieu provinces (Xuan and Van Mensvoort 1994). This zone occupies 800,000 ha, with mostly slightly or moderately acid sulfate soils. Salinity intrusion lasts for 5 to 6 mo (from December to May). During the wet season, the area can be inundated from 0.3 to 0.5 m because of stagnant rainwater. Agriculture in this zone is mainly rainfed with two rice crops per year. In some places, the summer-autumn rice crop is followed by an upland crop such as watermelon, onion, maize, or other vegetables that are grown by using the residual soil moisture after the rainy season.

Direct-seeding practices in different agroecological zones in the Mekong Delta

Zero-tillage direct seeding in the fresh-water alluvium zone

Zero-tillage direct seeding is often applied for the early summer-autumn crop on acid sulfate soils with shallow flooded areas of the fresh-water alluvium zone. Neither plowing, harrowing, or puddling is practiced before broadcasting. Several steps are required for preparing zero-tillage seeding fields. Immediately after harvesting the winter-spring rice in February (dry-season peak), all the rice straw is spread evenly over the entire field, covering the dry stubbles. The straw is burned right away, leaving a film of black ash over the field. In some cases, farmers wait a few days until the land is completely dry before burning the straw. Pregerminated rice seeds are broadcast directly into the ash; fresh irrigation water is brought into the field simultaneously. The field is drained after 24–36 h of flooding. A second irrigation is applied 3 to 5 d after seeding and the water level is kept at 3–5-cm depth.

Zero-tillage direct seeding represents excellent indigenous knowledge of local farmers. This technique was initially used in acid sulfate soil areas at Cai Be and Cai Lay (Fig. 1) to avoid acidity in shallow-flooded areas. Using the zero-tillage seeding method allows the summer-autumn crop to start early, in February. During this period, field water is still fresh and the rice plant can grow well. Poorer seedlings are observed in fields with acid sulfate soil when sowing is delayed until March or April because the field water is influenced by acidity as the river flow is reduced (in May, pH values range from 4 to 5). Because of its ability to reduce the turnaround time between crops, zero-tillage direct seeding is now widely practiced to establish dry-season crops in the three-rice area of the shallowly flooded zone (Fig. 3). One of the requirements of the system is water availability during the dry season. Dung (1987) reported that water availability was the predominant factor affecting the success and farmers' choice of this technique. Yields were positively correlated ($r = 0.29^*$) with nearness to a water source (canal). The pH of the water in paddy fields varied during the cropping season from 6–7 at 10 d after broadcasting (February) to 4–5 from 30 d after broadcasting onward (March). At this stage, however, young rice plants were not affected.

In an earlier survey conducted by Tai (1986), common soils of paddy fields under zero-tillage seeding in Cai Be were classified as clay loam soils with a humus content of 2%, total N of 0.1% to 0.25%, medium P and K, and 62.8% clay. Soils become hard after drying; in contact with water, the soil breaks up easily and soon becomes granulated to allow root establishment of young rice plants.

Rice varieties for zero-tillage direct seeding are mostly modern varieties with short duration such as IR50404, IR50401, IR12340-10-1, OM90-7, OM1706, IR9729, and IR59606. They perform best in both winter-spring and summer-autumn crops under zero-tillage direct seeding. The average seeding rate in Cai Lay is 230 kg ha^{-1}. Field surveys indicated that 200 kg ha^{-1} appears to be the optimum for zero-tillage direct seeding (Tai 1986, Dung 1987). Weed density in zero-tillage seeding fields is not high because the fields are burned. Yamauchi et al (1995) also reported that burning rice straw in zero-tillage systems prevents ratoon crops and weeds. And, because the turnaround time between the two crops is short, no weed control is required at sowing. A high fertilizer rate is used in farmers' fields for the zero-tillage seeding method. For example, the amount of fertilizer applied in this system is as high as 130 kg N ha^{-1}, 49 kg P_2O_5 ha^{-1}, and 19 kg K_2O ha^{-1}. The amount of fertilizer N applied and the grain yield in zero-tillage seeding fields are positively correlated with $r = 0.31^*$ (Dung 1987).

Water seeding in flood-prone areas affected by acid sulfate soils in the Plain of Reeds and Trans-Bassac Depression zone

In water seeding, pregerminated rice seeds are broadcast onto the flooded field. This technique is used for the winter-spring or autumn-winter crop in areas subject to annual deep flooding. Land is prepared for water seeding before the flood comes. After the previous crop is harvested, the field is harrowed twice and then left fallow under the floodwater. From November, the floodwater gradually recedes. When water recedes to about 30–50-cm depth, pregerminated seed is broadcast. To improve early growth of seedlings, farmers rake the soil under the submerged water just before seeding. This removes the algal mat, which formed during the flood fallow period. Sometimes the field is harrowed before broadcasting under deepwater conditions.

In the past, most areas in these two zones were under deepwater rice or fallow. In the early 1980s, government efforts aimed at intensifying cropping. As a result, part of these areas shifted to two rice crops per year. As the flooding period was prolonged from August to December (Fig. 3), only two rice crops could be grown from November to July of the following year. In fields where drainage conditions are difficult, farmers have to wait until the floodwater recedes completely in December or January before they can sow the winter-spring crop. Harvesting is done in March or April. The second crop starts in April-May and can be harvested in August-September. The second crop is often lost when the flood comes early. Farmers use the water-seeding technique to cope with this constraint. Direct seeding on shallow water allows farmers to start the winter-spring crop as early as November, when the floodwater is still receding, and to harvest the crop as early as February. This allows the second crop to be sown in March and to be harvested safely in June or July, thus escaping damage from early floods.

Research by Phuoc (1983) indicates that the water level at seeding time strongly affects grain yield: yield decreases from 4.3 t ha^{-1} at a depth of 20 cm to 3.2 t ha^{-1} at a depth of 30 cm at seeding time. A water level of 20–30 cm is most suitable for submergence seeding (Xuan 1984). Water seeding is practiced only in acid sulfate fields where the field water is clear. Turbid water may deposit sediments on seeds and block the light, which may interfere with emergence. Varieties for water seeding are short-duration ones such as IR50404, IR50401, IR12340-10-1, OM90-7, OM1706, and IR9729. An average seeding rate of 250 kg ha^{-1} was observed for water direct seeding at the Co Do farm (Fig. 1). Several farmers use high seeding rates (300 kg ha^{-1}) to ensure crop establishment and reduce weed infestation. Fertilizer application rates are 92 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 15 kg K_2O ha^{-1}. Weed density in water direct-seeding fields is less because the field is flooded. In water-seeding fields, golden apple snails, other fish, crabs, and other pests present a serious problem because they damage the rice plant during the young stage. Farmers use heavy insecticide application rates to achieve successful crop establishment. The area for water seeding is now shrinking because of biological stress (e.g., golden apple snails). The government also discourages the use of high doses of insecticides because they create pollution and harm the environment.

Dry seeding in rainfed coastal and acid sulfate soil areas

Dry direct seeding for the summer-autumn crop has been practiced on most rainfed fields, including coastal and acid sulfate soil areas. In this method, ungerminated rice seeds are broadcast onto the dry soil. Broadcasting is done before the onset of the rainy season, often in May. For dry direct seeding, farmers start preparing the land during the dry season in February or March. The field is plowed under dry soil conditions using a four-wheel tractor with a disk plow. The second plowing and harrowing are done after seed broadcasting to pulverize soil clods and to cover rice seeds.

Most soils in rainfed coastal areas have a heavy clay texture and are rich in humus and total N, but may have a high salt content because of salinity intrusion during the dry season. In this zone, the rainy season lasts 6 to 7 mo from May to October or November and rainfall is relatively high (1,500–2,000 mm per year). Farmers practice wetland preparation for the summer-autumn crop. They have to wait until late July because the remaining rainfall is not adequate to support two rice crops. Dry direct seeding helps farmers cope with water shortage and increase cropping intensity. It permits the use of early rainfall to establish the summer-autumn crop and allows the crop to be harvested as early as August. This early harvest leaves enough time and rainfall to support another rainfed crop. My et al (1995) reported that the possibility of having a second crop is the main reason for applying the dry direct-seeding technique. Perhaps the most important reason is that dry seeding provides a better way to cope with the irregular water supply.

For example, on thousands of hectares of rainfed ecosystems found in Vinh Loi and My Xuyen districts (Fig. 1), the summer-autumn rice crop was predominantly dry direct-seeded. With the improvement of water management, which reduces the saline period and increases fresh-water availability, farmers can now practice ordinary wet seeding instead of dry direct seeding.

Rice varieties for dry direct seeding are mostly modern varieties with short growth duration such as IR50404, IR50401, OM90-7, OM1706, IR42, and MTL199. IR42 performs best in rainfed coastal areas, especially on salinity-affected soils. In My Xuyen, farmers use a high seeding rate of 250 kg ha^{-1} to reduce weed infestation and use herbicides to control weeds. Pest and disease control receive special attention. Farmers apply 100 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 15 kg K_2O ha^{-1}. Currently, in dry direct-seeded fields, weedy rice is the most serious problem that limits yield. New short-duration varieties, which are suitable for rainfed conditions and high weed competition, are needed.

Good crop stand establishment depends a great deal on rainfall distribution at the beginning of the season. In years when broadcast seeds fail to emerge because of insufficient rainfall, farmers have to resow seeds. Rice farmers who practice dry seeding often switch to other crop establishment methods when water availability is more assured.

Ordinary wet seeding on irrigated and no-problem soils

Ordinary wet seeding is the most common form of wet seeding in the Mekong Delta. Land is prepared under wet conditions, after which the field is drained. Pregerminated rice seeds are broadcast immediately onto puddled soil (when the soil surface is soft). Wet seeding is applied for the summer-autumn or winter-spring crop.

Ordinary wet seeding is popular in irrigated ecosystems where soil or water conditions provide no constraint. Farmers can practice wet seeding for all rice crops in the year when conditions allow. Currently, because of the advantages of the zero-tillage seeding method, some farmers adopt it for the spring-autumn crop and adopt wet seeding for the winter-spring and summer-autumn crops. The most common cropping calendar in these areas is as follows: the winter-spring crop lasts from November to February, spring-autumn from February/March to May/June, and summer-autumn from June to September (Fig. 3).

Most farmers use varieties with short growth duration (e.g., IR50404, IR50401, IR12340-10-1, OM90-7, OM90-2, OM1706, IR9729, IR59606, IR13240-108, and IR64) for wet seeding. The average seeding rate is 200 kg ha^{-1} for wet direct seeding as in Cantho and Cai Lay. On average, the seeding rate of ordinary wet direct seeding is 19% lower than with other direct-seeding methods. Fertilizer application in farmers' fields varies from 90 to 110 kg N ha^{-1}, 40 to 45 kg P_2O_5 ha^{-1}, and 15 to 20 kg K_2O ha^{-1}.

Trends in yield and income from different direct-seeding techniques

During the 1980s and '90s, rice production under direct seeding strongly intensified as a result of adopting the technique. The increase in inputs, water management, and improvement of varieties led to a steady increase in yields. Table 1 shows the average grain yield for different direct-seeding techniques and ecosystems. In general, the yielding ability of rice does not differ among direct-seeding methods but depends strongly on the cropping season. In water direct seeding and ordinary wet seeding, the winter-spring rice crop produces the highest yield, from 5.7 to 6.2 t ha^{-1}. Rice yield for the spring-summer and summer-autumn crops varies from 3.6 to 4.2 t ha^{-1}.

The winter-spring season is a favorable cropping season because of its relatively higher radiation and lower temperature. Farmers can obtain a high profit from this cropping season. Table 2 shows that the profit is highest from the winter-spring rice crop, ranging from 3.0 to 3.3 t ha^{-1} in rice equivalent. Differences in income among direct-seeding techniques were not clear because yield strongly depended on the cropping season. However, total production costs for the winter-spring rice crop were higher than with other crops. The equivalent of total production cost for the winter-spring rice crop ranged from 3.0 to 3.2 t ha^{-1}, whereas that for other cropping seasons ranged from 1.8 to 3.0 t ha^{-1}.

Conclusions

Direct-seeding methods have played an important role in the intensification of the Mekong Delta rice systems. These techniques facilitate crop establishment in a large area in a much shorter time than with transplanting. Rice land productivity and labor efficiency can be enhanced by the farmer's choice of an appropriate direct-seeding method, considering soil and hydrologic conditions of the field, availability of appropriate land preparation equipment, and irrigation-drainage systems. Farmers also modify methods of direct seeding to adapt to changes in environmental conditions.

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Table 1. Grain yield of different direct-seeding techniques by ecosystem.[a]

Location and water conditions	Cropping season	Type of direct seeding	Grain yield ($t\ ha^{-1}$)									Average ($t\ ha^{-1}$)
			1990	1991	1992	1993	1994	1995	1996	1997	1998	
Co Do farm												
(flood-prone;	Winter-spring	Water seeding	5.2	5.7	5.8	6.1	5.9	5.7	6.0	6.1	6.2	5.9
acid sulfate soil)	Summer-autumn	Wet seeding	4.1	3.9	4.3	3.8	4.6	4.1	4.1	4.3	4.5	4.2
Cai Lay												
(irrigated, shallow	Early summer-autumn	Zero tillage	3.8	3.8	3.8	5.1	5.0	5.2	5.0	5.0	5.2	4.7
flooding, alluvial,	Late summer-autumn	Zero tillage	3.5	3.5	3.5	3.6	4.0	4.2	4.5	4.5	4.5	4.0
and acid soil)	Winter-spring	Wet seeding	6.1	5.9	6.3	5.9	6.0	6.5	6.5	6.6	6.4	6.2
My Xuyen												
(rainfed; saline-	Summer-autumn	Dry seeding	3.6	3.7	3.4	4.1	3.9	4.5	3.8	4.0	4.3	3.9
affected acid soil)	Autumn-winter	Wet seeding	2.9	2.7	3.3	3.6	3.4	3.7	3.5	4.3	4.8	3.6
Cantho												
(irrigated; slightly	Winter-spring	Wet seeding	5.8	5.3	5.5	5.4	5.8	5.6	5.9	5.8	6.1	5.7
acid soil)	Spring-summer	Wet seeding	4.4	4.1	3.9	4.4	4.2	4.1	4.0	3.7	4.2	4.1
	Summer-autumn	Wet seeding	4.1	3.7	3.8	3.5	3.7	3.8	3.6	4.2	4.0	3.8

[a]Data from field surveys and provided by the Office of Agricultural and Rural Development of districts.

Table 2. Farmer income from different direct-seeding techniques by cropping season (values are in t ha^{-1})[a].

Cropping season	Type of direct seeding	1995			1996			1997			1998			Average		
		Yield (t ha^{-1})	Costs (t ha^{-1})	Income (t ha^{-1})	Yield (t ha^{-1})	Costs (t ha^{-1})	Income (t ha^{-1})	Yield (t ha^{-1})	Costs (t ha^{-1})	Income (t ha^{-1})	Yield (t ha^{-1})	Costs (t ha^{-1})	Income (t ha^{-1})	Yield (t ha^{-1})	Costs (t ha^{-1})	Income (t ha^{-1})
Codo farm																
Winter-spring	Water seeding	5.7	3.1	2.6	6.0	2.9	3.1	6.1	3.0	3.0	6.2	3.1	3.1	6.0	3.0	3.0
Summer-autumn	Wet seeding	4.2	3.0	1.2	4.1	2.7	1.4	4.5	3.0	1.4	5.0	3.0	2.0	4.5	2.9	1.5
Cai Lay																
Early summer-autumn	Zero tillage	5.2	2.7	2.5	4.6	2.1	2.4	5.0	1.5	3.4	5.2	2.7	2.5	5.0	2.3	2.7
Late summer-autumn	Zero tillage	4.4	2.0	2.4	4.6	1.7	2.9	4.7	1.7	3.0				4.6	1.8	2.8
Winter-spring	Wet seeding	6.5	3.3	3.2	6.5	3.2	3.3	6.5	2.9	3.6	6.5	3.6	2.9	6.5	3.2	3.2
My Xuyen																
Summer-autumn	Dry seeding							5.4	2.8	2.5	5.1	2.4	2.7	5.2	2.6	2.6
Autumn-winter	Wet seeding							4.0	3.0	9.8	4.1	3.0	1.1	4.0	3.0	1.0
Cantho																
Winter-spring	Wet seeding							6.0	3.1	2.8	6.1	3.0	3.1	6.0	3.0	3.0
Spring-summer	Wet seeding							4.1	2.1	2.0	4.2	2.2	2.0	4.1	2.1	2.0
Summer-autumn	Wet seeding							3.0	2.1	9.2	3.0	2.1	9.0	3.0	2.1	9.1

[a]Data from field surveys; values are averages from representative farmers.
Costs and income are expressed in terms of rice equivalents in t ha^{-1}.

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Notes

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Impact of direct seeding on rice cultivation: lessons from the Muda area of Malaysia

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Direct seeding has emerged as a viable alternative to transplanting in Malaysia. In the Muda area, direct seeding comprises four basic techniques: wet seeding, dry seeding, water seeding, and volunteer seeding. Wet and dry seeding have had a significant impact on rice cultivation practices in the Muda area since their introduction in the 1970s. Improvements in farm management, especially the refinement of land preparation and land leveling, the availability of pre- and postemergence herbicides with wide application windows, and the use of water pumps to solve localized irrigation and drainage problems by farmers themselves, all contribute to the yield-enhancing nature of direct seeding. Ninety-two percent of the Muda farmers reported that the yield of direct-seeded rice crops is superior to that of transplanted crops. General yield trends are in this order: wet seeding > dry seeding > volunteer seeding. Studies conducted in the Muda area indicate that the technological possibilities of raising rice yield potential would come from direct-seeded rice. In the face of water scarcity, dry seeding enables relatively earlier crop establishment compared with wet seeding and transplanting. Dry seeding also contributes significantly to maintaining high cropping intensity where irrigation supply is limited. Innovative farmers who practice dry seeding obtain an additional harvest from ratoon crops. A direct-seeded crop required only 34% of the total labor requirement of the transplanted crop. Farmers could rely substantially on their own family labor and their control over the timing of farming activities is enhanced. Dry seeding and wet seeding have also resulted in a significant cost reduction. On average, direct seeding has enabled Muda farmers to save 29% of the total cost of a transplanted crop. Among the various direct-seeding methods, production cost was in this order: volunteer seeding < dry seeding < wet seeding. However, continuous herbicide application in direct seeding has led to a weed shift and the development of herbicide-resistant biotypes. Lessons from the Muda area reveal that strengthening research and extension linkages and active participation of farmers in field studies are needed to achieve sustainable rice production under direct-seeded conditions.

Historically, uneven crop establishment coupled with heavy weed infestation, extensive bird damage, severe rodent attacks, and poor field water management were dominant constraints to the widespread adoption of direct seeding. However, over the previous two decades, the continuous refinement of crop establishment methods and improvements in technology transfer in direct-seeded rice have created a significant impact on crop performance in the Muda area (97,000 ha) of Malaysia. Currently, direct seeding is widely practiced in the Muda area, which is the largest rice granary in the country. Seasonally, approximately 96–99% of the Muda area is direct-seeded (Table 1, Fig. 1).

Direct-seeding culture has emerged as a viable alternative to transplanting in Malaysia. In the Muda area, direct seeding comprises four basic techniques: wet seeding, dry seeding, water seeding, and volunteer seeding. Wet and dry seeding have had a significant impact on rice cultivation practices in the area since their introduction in the 1970s. Improvements in farm management, especially the refinement of land preparation and land leveling, the availability of pre- and postemergence herbicides with wide application windows, and the use of water pumps to solve localized irrigation and drainage problems by farmers, all contribute to yield enhancement with direct seeding.

With water scarcity, dry seeding enables relatively earlier crop establishment compared with wet seeding and transplanting. The Muda Agricultural Development Authority's (MADA) experience indicates that, when severe drought drastically depletes reservoir water, the adoption of dry seeding contributes significantly to the sustainability of high cropping intensity (>190% y^{-1}).

This paper deals with the effects of the use of inputs and labor on the yield of direct-seeded rice in the Muda area.

Labor use

Traditionally, the availability of labor for rice cultivation depends on three major sources: hired labor, family labor, and communal labor. When transplanting was the predominant cultural practice, Muda farmers faced a seasonal labor shortage during two peak periods—at transplanting and harvesting. Available family labor was grossly inadequate to meet these seasonal demands. A high percentage of the hired labor moved to the Muda area from southern Thailand and Kelantan State to seek work in farming operations. The seasonal labor shortage was aggravated with the implementation of double cropping. The tight planting schedule created an increased demand

Table 1. Status of various types of direct-seeded culture adopted for the first-season rice crop in the Muda area, Malaysia, 1981-99 (000 ha).[a]

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Wet seeding	3.8 (92.1)	13.5 (72.7)	20.2 (58.7)	6.4 (14.5)	5.6 (20.1)	38.1 (64.1)	0.5 (0.6)	42.6 (51.0)	64.4 (85.2)	53.9 (65.0)	47.0 (51.0)	12.4 (13.5)	30.8 (33.5)	88.8 (96.4)	88.4 (92.2)	82.9 (86.9)	92.9 (96.8)	95.0 (99.1)	93.7 (97.5)
Dry seeding	0.2 (5.0)	3.6 (19.2)	6.0 (17.5)	4.0 (9.0)	4.6 (16.4)	9.6 (16.2)	52.4 (59.7)	24.9 (29.8)	8.4 (11.1)	24.9 (30.0)	44.2 (48.0)	78.4 (85.5)	59.8 (65.2)	3.1 (3.4)	7.3 (7.6)	12.4 (13.0)	3.0 (3.1)	0.8 (0.8)	2.1 (2.2)
Volunteer seeding	0.02 (2.9)	1.5 (8.1)	8.1 (23.8)	34.0 (76.5)	17.8 (63.6)	11.7 (19.7)	35.0 (39.8)	16.1 (19.3)	2.8 (3.7)	4.1 (5.0)	0.9 (1.0)	1.0 (1.1)	1.2 (1.3)	0.8 (0.2)	0.2 (0.2)	0.08 (0.1)	0.05 (0.1)	0.09 (0.1)	0.3 (0.3)
Total area under direct-seeded rice culture	4.1	18.6	34.3	44.4	28.0	59.4	87.9	83.6	75.6	82.9	92.1	91.8	91.8	92.1	95.8	95.4	95.9	95.9	96.1
Total area planted in the Muda area	90.2	89.5	89.2	83.1	90.7	91.0	88.9	92.2	92.4	92.6	92.5	92.3	92.7	96.8	97.1	96.5	96.4	96.3	96.3
Percentage of direct-seeded rice culture (%)	4.6	20.7	38.4	53.4	31.0	65.3	98.8	90.7	81.8	89.5	99.6	99.5	99.1	95.2	98.7	98.9	99.5	99.6	99.8

[a]Values in parentheses are percentages.

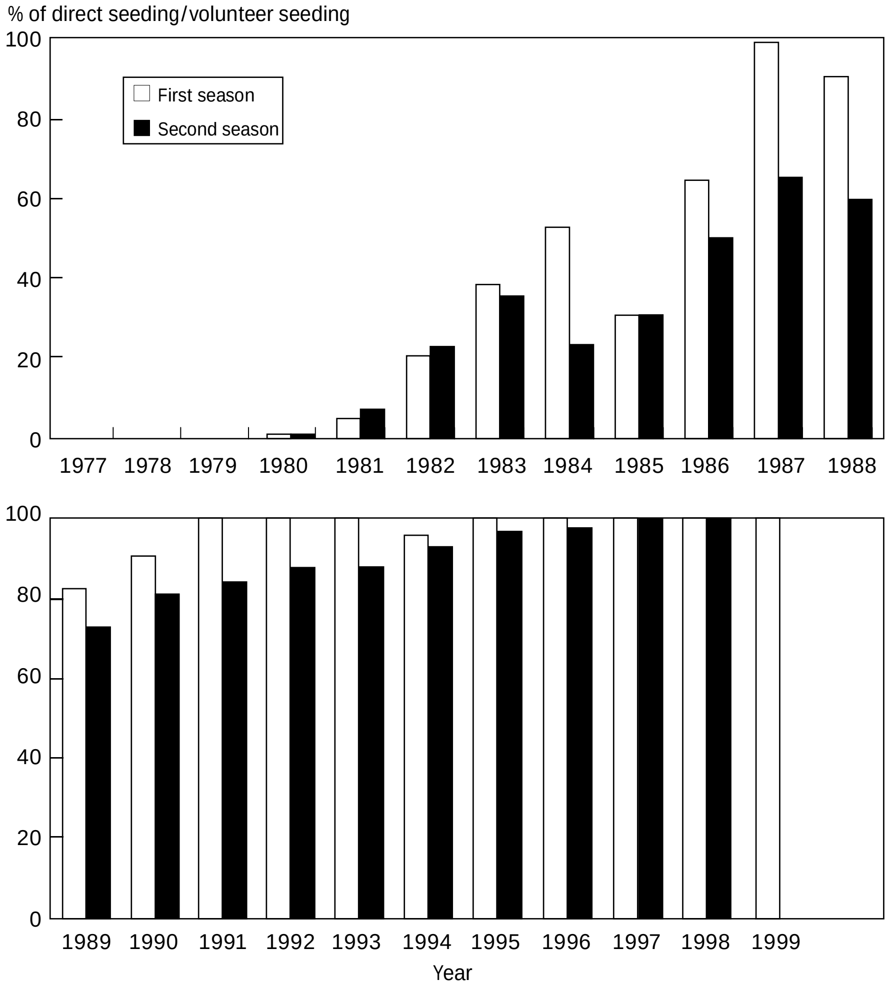

Fig. 1. Rice cultivation under direct-seeding and volunteer-seeding techniques in the Muda area.

for hired labor, which in turn pushed the wage rate up by 66% since 1972 (Afifuddin et al 1974).

The adoption of direct seeding offers an alternative approach for labor savings. Yeoh (1972) indicated that hand broadcasting of rice was 27 times faster than manual transplanting. Studies conducted by MADA revealed that manual transplanting requires approximately 140–200 person-h ha^{-1} compared with 7–10 person-h ha^{-1} for manual broadcasting and 2–4 person-h ha^{-1} for mechanical broadcasting (Ho 1999a).

The impact of technological changes on labor use in the Muda area is significant. Because of the increasing popularity and widespread adoption of farm mechanization and direct seeding, the seasonal labor requirement declined from 970 person-h ha^{-1} in 1970 to 261 person-h ha^{-1} in 1982. This drastic decline in labor requirement is attributable to three factors. First, land preparation was carried out by tractors (100% in 1982) instead of buffaloes (60% in 1970). Second, crop establishment was by direct seeding (21% in 1982) instead of transplanting (100% in 1970). Third, harvesting was done using combine harvesters (88% in 1982) instead of manually (100% in 1970) (Jegatheesan 1996).

Analytical studies on labor use by Wong and Morooka (1996) indicated that, on average, farmers using direct seeding used only 80 person-h ha^{-1} per season in 1988 compared with 237 person-h ha^{-1} per season for transplanting. This resulted in a labor savings of 157 person-h ha^{-1} per season. The direct-seeded crop required only 34% of the total labor requirement of 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 was significantly enhanced.

Another study conducted by MADA in 1991 showed that, in an abnormally dry season with no irrigation supply, the level of labor use for direct seeding would be higher. This was because farmers had to spend more time replanting vacant spots in fields. They also had to carry out more intensive weed control to avoid yield losses. Among the various direct-seeding techniques adopted, the seasonal labor requirement increased in the following order: volunteer seeding (137 person-h ha^{-1}) < dry seeding (158 person-h ha^{-1}) < wet seeding (212 person-h ha^{-1}). Differences are attributed to less labor used in land preparation and sowing (especially for volunteer seeding) as well as in water and crop management (Wong and Morooka 1996) (Fig. 2).

Under estate management, it is possible to achieve 5.9 t ha^{-1} with 180 person-h ha^{-1} in wet-seeded rice culture. This is because better farm supervision enhances the quality of land preparation. A significant savings in labor is obtainable through a reduced frequency of herbicide application resulting from good water management (Ho 1999a).

Input use and returns

The saving in production costs is another significant factor in encouraging farmers to switch from transplanting to direct seeding. An analysis of cash expenditure for transplanted and direct-seeded crops in the first season of 1988 in the Muda area indicated a total expenditure amounting to US$389 ha^{-1} for transplanting versus $278 ha^{-1} for direct seeding. On average, direct seeding has enabled Muda farmers to save $111 ha^{-1} or 29% of the total cost of a transplanted crop. The savings is in the transplanting operation. It costs an average of $91 to transplant 1 ha of rice through manual labor, which is predominantly hired labor. On the other hand, $3.20 was the average expenditure for direct seeding. Crop establishment cost was drastically reduced, by 28 times, with the introduction of direct seeding (Wong and Morooka 1996).

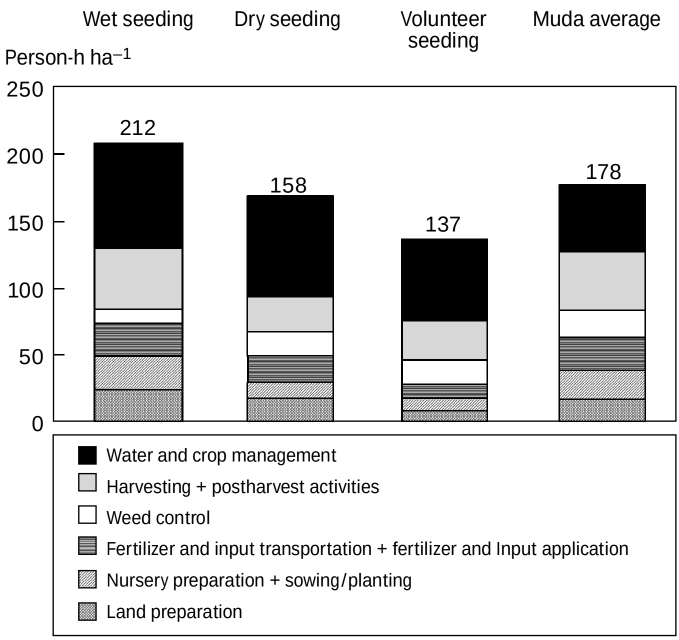

Fig. 2. Labor use (person-h ha^{-1}) by cropping method in the first season of 1991 (Wong and Morooka 1996).

Studies conducted by MADA in 1991 revealed that the production cost using various direct-seeding methods varied in the following order: volunteer seeding (\$177 ha^{-1}) < dry seeding (\$230 ha^{-1}) < wet seeding (\$278 ha^{-1}) (Wong and Morooka 1996).

In recent years, because of the pull of urban growth centers near farms, labor shortages have become more acute. To address the problems of declining labor supply and optimum farm input use, MADA began forming large-scale commercial rice farming projects in the Muda area. Farmers' organizations (FOs) supervised by MADA have been mobilized to become the main vehicle in implementing and managing these projects. The first rice estate was established in 1996, comprising 38 farm families operating 65 ha of rice land. The extension worker in the FO is appointed as the farm manager. He is assisted by a farm supervisor, whose monthly salary is paid from the operational fund provided by the rice estate. Four workers are selected from among the participating farmers, who are paid daily wages according to the work performed. The rice crop is entirely direct-seeded. The production cost in the second season of 1998 was \$321 ha^{-1}. In the Muda area, the average production cost for direct seeding in the same season was \$235 ha^{-1}. This means that the rice estate incurred an extra expense of \$85 ha^{-1} compared with the Muda average (Table 2). The additional expense was due to the more rigorous replacement of vacant spots and

Table 2. Comparison of production costs of direct-seeded rice between a rice estate and the average Muda farmer (1998 second season).

Item	Rice estate Kodiang, locality A-II (US$ ha^{-1})	Muda average (US$ ha^{-1})
Plowing	41.45	55.56
Clearing and repair of levees	9.21	2.36
Raking and leveling	9.21	13.89
Seed purchase and transportation	22.11	22.00
Seed broadcasting	9.21	4.56
Planting vacant spaces	36.84	0.61
Pumping water	–	0.58
Additional fertilizer	33.16	4.06
Transportation application of fertilizer	13.82	5.14
Insecticide/fungicide purchase and application	29.47	3.14
Herbicide purchase	28.55	24.26
Combine harvesting	59.87	66.39
Transportation, postharvest handling, and other miscellaneous expenditures	27.63	32.72
Total	320.53	235.27

purchase of additional fertilizer. However, substantial savings were realized on items such as land preparation and harvesting by strengthening the negotiating power of the estate management when dealing with machine contractors (Ho and Zainuddin 1999).

For rice yield, in the second season of 1998, the rice estate obtained an average yield of 5.9 t ha^{-1} compared with 4.9 t ha^{-1} in the entire Muda area. The additional 1 t rough rice per hectare was priced at \$261 t^{-1}. The net return under estate management was \$175 ha^{-1} more than that of the Muda average.

In the same season, the transplanted crop yielded 4.4 t ha^{-1} in the Muda area. The average production cost for transplanting was \$326 ha^{-1}. The net return under estate management was \$396 ha^{-1} more than that of the transplanted crop average (Fig. 3).

Yield performance

The instability of rice yield during the first decade (1980-90) of direct seeding in the Muda area has been attributed to severe water deficit, which led to a delayed irrigation water supply. Saturated soil conditions because of the uncontrolled moisture level in fields strongly favored the germination of grassy weeds. *Echinochloa crus-galli, E. colona, Leptochloa chinensis,* and *Ischaemum rugosum* were rampant in direct-seeded fields. Unchecked weed growth reduced grain yield by 30–100% (Ho 1994).

The crop cutting survey conducted in the first season of 1986 indicated that direct-seeded rice yielded 3.8 t ha^{-1} compared with 4.0 t ha^{-1} under transplanting (Ho

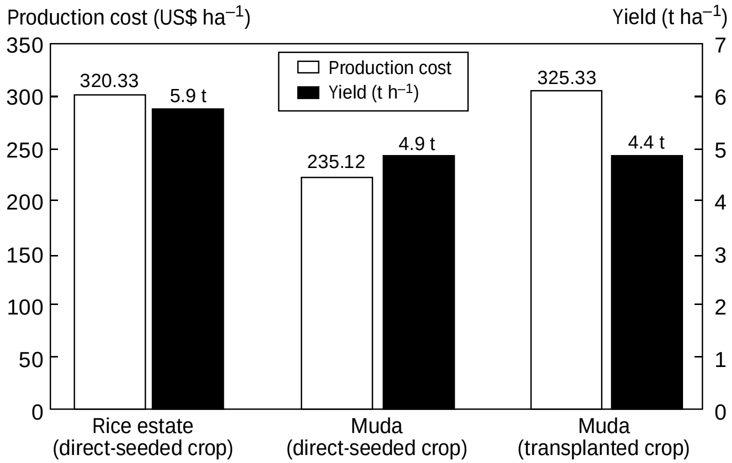

Fig. 3. Rice yields and production costs in the Muda area (second seasons 1998).

Table 3. Gross rice yields (t ha^{-1}) of different crop establishment methods of the first-season crops (1994-99) in the Muda area, Malaysia.

Item	1994	1995	1996	1997	1998	1999
Transplanting	4.1	3.6	4.4	3.4	4.0	4.2
	(26)[a]	(21)	(10)	(6)	(4)	(5)
Wet seeding	4.6	4.7	4.9	4.4	4.4	5.1
	(455)	(449)	(464)	(508)	(541)	(566)
Dry seeding	3.9	4.1	4.1	3.9	3.6	4.3
	(19)	(42)	(47)	(24)	(3)	(8)
Volunteer seeding	3.4	3.7	4.0	3.8	4.5	3.7
	(20)	(19)	(15)	(5)	(4)	(16)
Muda average	4.5	4.6	4.8	4.4	4.4	5.0
	(520)	(531)	(536)	(543)	(552)	(595)

[a]Numbers in parentheses denote sample sizes.
Source: Planning & Evaluation Division, MADA (Crop Cutting Survey Reports, season 1/94-1/99).

et al 1993), or a 5.3% lower yield in the direct-seeded crop than in the transplanted crop.

From the mid-1990s onward, because of the continuous improvement of crop and resource management at the farm level, rice yields in direct-seeded fields have been increasing steadily in the Muda area, surpassing yields of conventional transplanted rice. Table 3 clearly indicates the average seasonal yields of transplanted and direct-seeded plots taken from the crop cutting surveys. Results consistently show that, from 1994 to 1999, yields of wet-seeded plots were higher than those of transplanted fields by 11.2% (1996) to 31.2% (1997). Among the various methods of direct seeding, general yield decreased, with wet seeding > dry seeding > volunteer seeding, with the exception of 1998.

Relatively poorer transplanted rice yields in the Muda area could be attributed to generally suboptimal plant density (<16 hills m^{-2}), which led to a lower panicle number per unit area (<350 panicles m^{-2}). This was significantly lower than the average of 415–434 panicles m^{-2} under wet-seeded culture (Kobayashi et al 1999).

Recent advances in agronomic practices such as land preparation, land leveling, uniform seeding, and proper fertilization have enhanced the crop performance of direct seeding. In addition, improvement of the tertiary irrigation system and other on-farm water management as well as the widespread adoption of cost-efficient herbicides have contributed to a remarkable increase in rice yields. This improvement is clearly reflected in the crop cutting survey in 1999. For the first time after 30 years of rice double cropping, the average first-season yield in the Muda area reached 5.0 t ha^{-1}. In that season, 96,000 ha or 99% of the Muda area was direct-seeded. Many innovative farmers have achieved remarkable yields of 6–7 t ha^{-1}. The highest recorded yield of 9.5 t ha^{-1} was obtained by a farmer who practiced wet seeding.

Some innovative farmers are experimenting with water seeding to minimize yield losses caused by weedy rice infestation. Recent farm surveys also recorded some enterprising farmers who practiced dry seeding and who were able to obtain an additional harvest from a ratoon crop of short-maturing varieties. The ratoon crop yielded from 0.5 to 0.7 t ha^{-1}, providing farmers with an additional income of $132–184 ha^{-1}.

Lessons from using direct seeding

Labor use in the Muda area has changed dramatically over the past two decades after the widespread adoption of direct seeding. Labor-use patterns constrast greatly under different crop establishment methods. Transplanting is predominantly carried out by hired labor, whereas all activities in direct seeding—the soaking of seeds, seed transportation, broadcasting of seeds, and replacing seedlings in vacant spots—are mainly carried out by family labor. Direct seeding will continue to be the dominant crop establishment method in the 21st century.

Mechanical transplanters are not likely to be popular in the Muda area mainly because of their large capital investment and because seedling preparation is very labor-intensive. Despite the reduced labor requirement under direct seeding, the problem of labor scarcity will likely become more acute in the future. This is because rapid industrialization and the aspiration for an urban lifestyle among rural youths will aggravate the labor shortage at the farm level. Further, labor availability is also expected to decline because of an aging population. The average age of farmers has increased from 43 in 1966 (Tamin and Jegatheesan 1980) to 53 in 1991 (Wong 1992). Group farming and the formation of rice estates are feasible alternatives to reduce the labor requirement. The pilot rice estate projects have provided valuable opportunities for MADA management to gain insights into the detailed modus operandi of large-scale commercial rice cultivation and its implications. Pilot studies revealed that proper preproject explanation and an appropriately structured work plan are essential in convincing farmers of the advantages of estate operation compared with individual operation. Besides, incentives such as credit facilities and alternative income sources are essential in persuading farmers to hand over their farms to an external agency to operate. Tenant farmers who are displaced by the establishment of rice estates should be taken care of to minimize their resistance to the implementation of this concept (Ho and Zainuddin 1999).

Technological innovations in rice cultivation have resulted in rapid changes in the crop habitat, triggering a chain reaction in the rice agroecosystem. The widespread shift in crop establishment method from transplanting to direct seeding since 1980 has caused drastic changes in the weed spectrum in the Muda area. After three consecutive seasons of direct seeding, serious infestation of *Echinochloa crus-galli* was observed. This was followed by the infestation of *Leptochloa chinensis* (after 10 consecutive seasons), *Ischaemum rugosum* (after 14 consecutive seasons), and weedy rice (after 20 consecutive seasons) (Ho 1996).

In the Muda area, rice weed management is not expected to differ markedly from current practices. Nevertheless, the area treated with herbicide is expected to expand because of weed shifts and the development of herbicide resistance. Reliance on a single herbicide has been shown to result in quantitative changes in the structure of the weed population. Herbicide-tolerant or resistant biotypes could evolve through repeated use of the same herbicide over a long period (Ho 1996). Realizing the far-reaching impact of continuous herbicide use in direct-seeded rice, MADA has adopted the concept of farmer participatory weed management to encourage and facilitate the adoption of ecologically sustainable technology at the farm level. In a pilot study carried out by MADA, farmers were trained to conduct simplified survey methods for rapid weed assessment in their own fields. They were subsequently educated on the importance of herbicide rotation in minimizing weed shifts and herbicide resistance problems. Participating farmers were encouraged to conduct their own field experiments using several herbicide combinations to replace the bensulfuron + metsulfuron mixture, which has caused a serious weed shift in favor of *Bacopa rotundifolia* in direct-seeded fields.

After applying herbicides, farmers were requested to repeat the simplified weed survey in treated areas to compare weed dominance and evaluate the performance of various herbicides. Farmer participatory experiments on herbicide rotation have proven to be very effective in overcoming weed shift problems in the pilot study. They also helped to sharpen farmers' perceptions in making more rational decisions on weed management (Ho 1999b).

Conclusions

When direct seeding was still new, rice yields fluctuated sharply because of limited farmers' knowledge on crop management, poor weed control, and the use of inappropriate cultivars. Some researchers expressed reservations because they believed that low yields and unstable rice production were the result of the expansion of direct seeding in Malaysia. However, continuous refinement of management innovations and technology transfer over the past 20 years have allowed Muda farmers to achieve stable rice yields using direct seeding. An analysis of the historical profile of crop establishment methods indicates clearly that direct seeding will continue to be the main method used in the Muda area in the years to come. The popularity of direct seeding is due mainly to practicality, convenience, and economic benefits associated with this method. A recent study indicated that 92% of Muda farmers believed that the yield performance of a direct-seeded crop was superior to that of a transplanted rice crop. Furthermore, its labor cost–saving advantage more than compensated for the increase in herbicide cost because of direct seeding. Improvements in land preparation and land leveling, the availability of postemergence herbicide with wide application windows, the use of water pumps to solve localized irrigation and drainage problems by farmers, and the mobilization of dynamic action groups all contributed to the yield-enhancing effects of direct seeding in the Muda area (Ho et al 1999a).

In the 21st century, farmers will unlikely revert to transplanting because direct seeding, with its associated mechanization of farm operations, has alleviated the drudgery of manual work. Efforts must be undertaken to ensure that problems associated with the continuous practice of direct seeding will not have adverse effects on the environment. A closer linkage between research and extension is necessary. Collaborative efforts should focus more on herbicide residues and their impact on natural enemies and beneficial organisms as well as soil microorganisms in the rice ecosystem.

Lodging is common in the direct-seeded crop. Yield loss could be substantial for cultivars with tall, top-heavy, and weak culms. More research should concentrate on developing cultivars with intermediate height, erect leaves, and compact panicles with deep rooting.

Conventional agricultural extension activities are labor-intensive. It has been estimated that, at most, extension technicians can serve from 50 to 100 families regularly (Hornik 1988). Currently, in the Muda area, the extension agent to farmer ratio is 1:1,000. It is imperative to promote the farmer-to-farmer extension approach. Farmers' participatory experiments could contribute significantly to helping researchers and extension agents verify new crop management technology more efficiently in location-specific areas.

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Farmers' direct-sowing practices in rainfed lowland rice in southern Thailand: improving a traditional system

G. Trébuil and S. Thungwa

For many decades, dry seeding was the dominant farmers' practice for establishing rainfed lowland rice (RLR) in the drought- and submergence-prone areas bordering the Songkhla lagoon along the eastern coast of southern Thailand. Because of the highly constraining soil-water complex, RLR growers have been combining an array of dry-seeding and transplanting practices adapted to varying soil and climatic conditions to be able to grow rice in their fields every year, although with a relatively low but rather stable crop productivity.

During the past decades, RLR dry-seeding techniques dominated the three main types of household-based farming systems, while paddy fields most infested by weeds, particularly wild rice, were transplanted. Land preparation and crop establishment on heavy-textured soils, water depth control, and weed infestation, especially by wild rice, were found to be major interrelated problems that can be addressed by strategic and applied research to stabilize yields and increase labor productivity of local dry-seeded rice systems.

Labor productivity in dry-seeded paddies is often very low because of the tedious and highly time-consuming hand-weeding and thinning-transplanting practice. At least 50 d ha^{-1} are needed to achieve an RLR yield of more than 2.2 t ha^{-1} and 150 d ha^{-1} in wild rice-infested fields for effective control by using the integrated approach designed over time by farmers. Agronomic and economic results of on-farm experiments on land preparation and row seeding demonstrate the potential of this technique in high weed-infestation situations.

Recently, a limited crop diversification scheme based on integrated systems of small-scale crop-fish rearing led to an improvement in the capture of water and supplementary irrigation. During the 1987-96 decade of high economic growth, the scarcity of farm labor increased because off-farm employment opportunities were more attractive and readily available. As a consequence, in association with adopting new early maturing cultivars and combined with mechanizing the RLR harvest, an important increase in wet-seeded rice has been observed since 1996.

For many decades, dry seeding was the dominant farmers' practice for establishing rainfed lowland rice in the drought- and submergence-prone areas bordering the Songkhla lagoon along the eastern coast of southern Thailand. Because of the highly constraining soil-water complex, rainfed lowland rice (RLR) growers developed dry-seeding practices adapted to varying soil and climatic conditions to grow rice in their fields every year, although with a relatively low but rather stable crop productivity (Trébuil 1987, 1988, Pandey and Velasco, this volume). On-farm diagnostic surveys carried out in the area in the 1980s found that land preparation of heavy-textured soils, RLR crop establishment techniques, water depth control, and weed infestation, especially by wild rice, were major and interrelated limiting factors in RLR production (Crozat and Chitapong 1988, Trébuil et al 1984). This article summarizes the main findings of a series of on-farm research studies carried out in Sathing Phra District of Songkhla Province. It has the following objectives:

1. To analyze farmers' practices and strategies regarding the selection of crop establishment techniques in RLR,
2. To quantify the effects of these techniques and other related cultivation practices on RLR yields and labor productivity,
3. To assess the potential of row seeding in medium RLR paddies,
4. To understand recent local patterns of change in RLR crop establishment methods, and
5. To identify key strategic and applied research issues for improving local RLR production.

Materials and methods

An in-depth and comprehensive on-farm diagnostic analysis of the Sathing Phra agrarian system was carried out during the 1982-83 wet season (WS) (Trébuil 1984, 1987). Following the on-farm testing of innovations for the two main economic activities in the area—RLR production during the wet season (July-February) and palm sugar production during the dry and prehumid seasons (January-June)—the evaluation of their impact and a rapid appraisal of changes in the functioning of the farming systems were implemented during the 1987-88 WS (Trébuil 1988).

On-farm experiments on land preparation and row seeding carried out in 1987-88 compared dry-seeded rice (DSR) plots established by manual broadcasting (BC, the most frequently used farmers' practice) and row seeding (RS) on six farms. The IRRI-designed two-row seeder was pulled by a hand tractor equipped with caged wheels. Observations were gathered on sowing densities, RLR plant densities at emergence and at harvest, degree of weed infestation, weeding practices, monitoring of floodwater level, and RLR yield. All variable and fixed costs for both crop establishment techniques were recorded to carry out a partial budgeting analysis (Harrington et al 1986). This type of economic analysis was conducted to help identify RLR crop situations in which the row seeder could significantly help farmers achieve their economic objectives. Costs that vary between RS and BC treatments were first estimated, then benefits and marginal rates of return to capital were calculated. The effects of the RS technique on labor productivity (value added per unit of labor) were also assessed.

A rapid appraisal survey was carried out in January 2000 to update information from previous diagnostic studies in the same three villages located along an east-west transect in the most diverse southern part of Sathing Phra District. This time, the survey emphasized the identification of recent changes in RLR crop establishment practices and their interpretation through the analysis of transformations of biophysical and socioeconomic conditions of agricultural production in this area. Runs of transects crossing the main rice-based agroecological units of the landscape and farmers' interviews were used to collect information on these topics.

Agroecological characterization of the study area

Located on a narrow peninsula between the Gulf of Thailand and the Songkhla lagoon, the RLR growing area of densely populated Sathing Phra District, with more than 400 inhabitants km^{-2}, is a drought- (at vegetative stage from July to September) and submergence-prone (during the peak of the rainy season in November-December) ecosystem with a very constraining soil-water complex. Apart from the narrow sand bars to the east on which limited rice production in upper paddies is done (mainly dry-seeded nurseries, which are later only thinned or completely pulled and transplanted, accounting for some 3% of the RLR area), RLR is mainly grown in medium paddies on very heavy soils with slow drainage, and a clay content of more than 40%, where the crop is closely associated with sugar palms. Medium paddies represent some 85% of the total RLR area and lower paddies on very heavy soils with a clay content of more than 60% located in low-lying, submergence-prone areas, and without sugar palms associated with rice, make up the remaining 12% of the local RLR planted area.

The onset of the wet season in this area is very unpredictable and, in some years, the prehumid season, during which rainfall is less than potential evapotranspiration (PET) but more than half of PET, can last from April to September (Crozat et al 1985). As most of the total annual rainfall is concentrated over the last three months of the year, farmers have developed many climatic risk avoidance strategies and practices to cope with such conditions, which allow them to establish RLR and some deepwater rice (in agroecological unit 3) every year in all their fields.

Main types of rice-based farming systems

Based on farmers' socioeconomic strategies and availability of land, labor, and capital resources, three main types of farming systems can be distinguished (Trébuil 1988):

- Type I: very small farms (0.3 to 0.4 ha per unit of labor) where, year-round, most of the family workforce is employed in nonrice economic activities to maximize family labor income, such as palm sugar production, but also for more and more

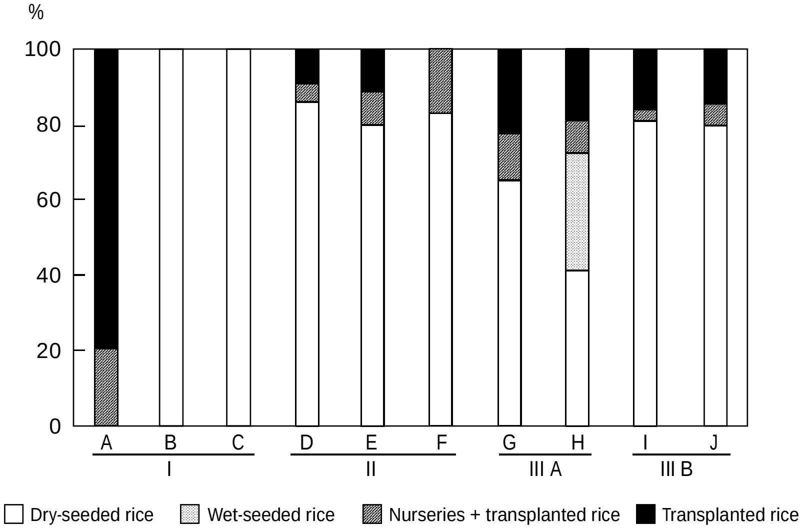

Fig. 1. Percentage of the rainfed lowland rice area per crop establishment technique and by type of farmer (I, II, IIIA, IIIB) on 10 farms (A to J) in Sathing Phra, southern Thailand.

wage-earning activities, especially in Songkhla-area canning factories for sea products. For this reason, farmers' paddy fields are either transplanted in the case of very small farms or totally dry seeded (Fig. 1). Rice production here is exclusively for family consumption. Depending on the village, 50–60% of the total number of farms in the area belong to this type. Because of the limited role of RLR on these tiny farm holdings, improving their production is not a priority to households.

- Type II: medium-sized farms (0.5 to 0.8 ha per unit of labor) with few nonrice activities during the wet season. Labor productivity in RLR is very low because of intensive hand weeding, thinning, and seedling redistribution implemented in dry-season (DS) plots by family labor (up to 200 person-d ha^{-1}), except in remote fields. Only 16% of those remote fields were hand-weeded during the 1982-83 WS versus 86% for fields located a short distance away from the village. Cattle rearing, with weeds from RLR fields as a major source of forage during the wet season, is another common activity on these farms that market up to 50% of their rice production. Depending on the village, 25–40% of the farms belong to this type of farming system.
- Type III: larger, more productive farms where intensive rice production techniques have been introduced, such as wet seeding or transplanting of shorter duration recommended varieties that were grown on 50% of their paddy fields in the early 1980s to increase the net benefit per land unit (subtype IIIA). A more labor-extensive rice production system is adopted on the largest holdings with

more than 0.8 ha per unit of labor and up to 8 ha per unit of labor (subtype IIIB). Because maximizing productivity of scarce labor resources is the farmers' key management criterion here, few days are spent hand weeding rice fields; 10–15% of farms belong to this type and farmers sell more than half of their rice produce on the market.

Each farm has access to several RLR fields distributed across the three different main agroecological units, where different RLR production techniques are implemented to suit field hydrological conditions to limit the risk of crop failure, and to stagger labor requirements during land preparation, crop establishment, weeding-thinning-seedling redistribution in DSR fields, and harvest. Because of differing management strategies and the relative importance of RLR in the main farming systems, efforts to improve RLR cropping systems focus on farm types II and III.

Results and discussion

During the 1980s, direct dry seeding was the dominant type of RLR crop establishment technique for all three types of farming systems. This could be explained by the general absence of water control that limited the duration of optimal field conditions for transplanting. As a consequence, during the 1982-83 WS, only 20% of the area planted to RLR was transplanted, generally with early maturing recommended varieties, and mainly on type III farms employing a significant amount of hired labor. In that period, 90% of the fields planted to the most popular local photoperiod-sensitive RLR cultivar, called "Sali," were dry-seeded, especially on farm types I and II.

Diversity of crop establishment practices traditionally dominated by DSR

Based on results from the extensive RLR field monitoring survey carried out in the early 1980s, Table 1 summarizes the important diversity of sets of cultivation practices selected by farmers. Such a wide variability in farmers' practices is due to unpredictable climatic conditions and lack of good water control at the field level. Depending on the type of equipment used (tractor, hand-tractor, oxen), the number of passes (from one to three), and type of sowing technique adopted (broadcast seeds plowed in when sowing during a rainy period, or not covered in the case of predominantly drier weather conditions), as many as seven different major patterns of cultivation practice were used to establish DSR on farms belonging to types II and III. When all successive techniques (different types of nurseries, farm equipment, etc.) involved in crop establishment were taken into account, 21 patterns were found.

In Sathing Phra District, farmers were using 64 different RLR varieties. These varieties displayed very different crop cycle durations (from 4 to more than 7 months), but a tendency toward selecting more early maturing cultivars was observed on most of the farms during the 1980s (Trébuil 1987) and again since 1996. In broadcasting, seeding rate was higher where seeds were covered by a second pass of the plow or by harrowing (51 kg ha^{-1}) than where seeds were not covered (39 kg ha^{-1}). This latter

Table 1. Characterization of the diversity of cultivation practices in RLR fields of Sathing Phra, southern Thailand. Data collected from 158 paddy fields belonging to 10 farmers, 1982-83 wet season.

Type of RLR subecosystem	RLR cultivars (no.)	Crop establishment techniques[a] (period)	% area per RLR subecosystem	Hand weeding time (min.-max., d ha^{-1})	Mineral fertilization (min.-max., kg N ha^{-1})
Upper paddies	3	1	24		
		3	64	0–80	0–32
		4	12		
		(Sep–Oct)			
Medium paddies	19	1	73		
		2	4	0–190	0–66
		3	19		
		4	4		
		(July–Oct)			
Lower paddies	7	1			95
		3	5	0–125	16–80
		(July–Aug)			

[a]Crop establishment techniques: 1 = dry-seeded rice (DSR), 2 = wet-seeded rice, 3 = transplanted rice (TPR), 4 = partially pulled nursery. Partially pulled nurseries are dry-seeded nurseries in which farmers pull only the number of seedlings they need for transplanting in TPR fields or to fill gaps in DSR fields. The remaining seedlings are left to complete their vegetative cycle until harvest.

practice is followed by farmers who anticipate a predominantly dry climate during the following days. This is because, for plowed-in BC seeds, the emergence rate is lower because of losses in seeds located deeply between clods.

Figure 1 shows the extent of the different kinds of RLR crop establishment techniques according to the type of household-based production system. The figure also shows that, apart from TPR fields, a significant share of the RLR seedlings produced in nurseries are used to fill gaps in DSR fields as well, especially in farm type II and IIIA paddies. Apart from the tiniest rice holdings belonging to type I that are not self-sufficient, DSR was the preferred technique used by farmers in 75% of the RLR planted area. The early maturing recommended cultivars are planted in September, after the local more drought-tolerant ones have been planted. This practice decreases the risk of drought during the vegetative phase of the crop cycle (Table 2).

Although only a few type III farmers were introducing WSR in the early 1980s on 5% of the RLR area, the remaining paddy fields were transplanted in October-November. To stagger work on the farm, transplanting of early maturing recommended varieties is carried out during the period between establishing DSR fields and hand weeding–thinning–seedling redistribution in those dry-seeded plots. Usually, transplanted rice (TPR) is found in fields most infested by weeds, especially wild rice, following several crop cycles of DSR. The farmers' practice of minimum land preparation (one pass with an oxen or disk plow) and early broadcasting of DSR usually leads to heavy weed infestations in years with a late onset of the rainy season. Highly time-consuming hand weeding, usually combined with thinning-replanting, is generally needed to homogenize the plant population in DSR. This can only be done during a limited period

Table 2. Risk of drought during the early vegetative phase in dry-seeded paddies of the two main rainfed lowland rice (RLR) subecosystems of Sathing Phra, southern Thailand.

RLR subecosystem (amount of water available) and type of cultivar	RLR sowing date	Probability of drought stress[a] before tillering[b]
Medium paddies (300 mm)	11 Sep	0.52
Medium-maturing varieties	21 Sep	0.24
(150–160 d)	1 Oct	0.08
Lower paddies (550 mm)	11 Sep	0.64
Late-maturing varieties	21 Sep	0.52
(180–200 d)	1 Oct	0.24

[a]Soil moisture at less than field capacity during the first three 10-d periods after sowing. [b]Water balance calculated for 25 y from rainfall and potential evapotranspiration, with losses from percolation and capillarity estimated at 1 mm d^{-1} and soil moisture content at sowing equal to wilting point.
Source: adapted from Crozat et al (1985).

determined by soil-water conditions. It can begin on clayey soils as soon as field capacity is reached but it has to be stopped when fields are flooded. For this reason, hand weeding tends to start late, generally 45 to 60 d after sowing, and after wet seeding and transplanting work are completed. Lower RLR paddies are the first to be flooded and hand-weeded, but every year only part of the fields can be completely hand-weeded as the number of suitable days and amount of labor for weeding-thinning-seedling redistribution are limited, even on type II farms. Consequently, the quality of land preparation and initial RLR crop establishment, by limiting the requirement for hand weeding-thinning-seedling redistribution ("plot repair" work in farmers' words), can play an important role in the performance of RLR at the field and farm levels.

Figure 2 shows the amount of weeding time spent by farmers in their RLR paddies according to each of the three main types of farming systems. Type III holdings, with less labor available per hectare, tend to spend less time in hand weeding fields than type II farms, with less alternative employment opportunities during the wet season. Table 3 also shows the distribution of time spent in hand weeding-thinning-seedling redistribution in RLR fields. Data show that, depending on the year, one-third to one-half of DSR fields required more than 100 person-d ha^{-1} for weeding. When no hand weeding-thinning-seedling redistribution at all can be done, such as in remote rice fields, yield losses varied from 25% to 50% compared with weeded plots, depending on the type and intensity of the weed competition (Trébuil 1987). Among local DSR medium paddies, in terms of plant density, all transitional stages between a dry-seeded field and a dry-seeded nursery (established following the same land preparation and sowing techniques, with only a much higher seeding rate) can be found depending on the number of seedlings being pulled for use in other fields after the start of the rainy season. Mineral fertilization of DSR partly depends on the hand weeding-thinning-seedling redistribution practice. If weeding can be completed on time, a second fertilizer application is usually made, following the first one at sowing or, more often, at the tillering stage. But the second one is cancelled if weed control cannot be done properly, leading to a drop in RLR productivity.

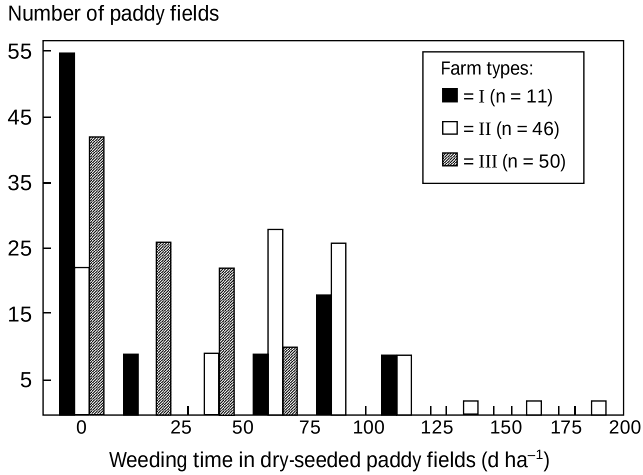

Fig. 2. Hand-weeding time in dry-seeded paddy fields for the three main types of farming systems (I, II, III) in Sathing Phra, southern Thailand, 1982-83 wet season.

Table 3. Distribution of working time (% of fields) spent in hand weeding–thinning–seedling redistribution in direct-sown rainfed lowland rice fields of Sathing Phra, southern Thailand.

Crop year[a]	Person-d ha^{-1}	0–19	20–39	40–79	80–99	100–149	> 150
1982-83 WS		28	8	9	8	22	25
1984-85 WS		5	10	40	13	13	19

[a]Data came from 88 fields during 1982-83 wet season (WS) and 22 fields during 1984-85 WS.

Variability of RLR crop productivity

Maximum yields achieved by farmers for each of the three main types of RLR subecosystems were 1.9, 2.5, and 4.2 t ha^{-1} for upper/sandy, lower/very clayey and submergence-prone, and medium/clayey paddies, respectively. In the 1982-83 WS, the average local RLR paddy yield was 1.8 t ha^{-1}. A minimum of 50 person-d ha^{-1} for hand weeding-thinning-seedling redistribution was needed to achieve a yield of 2.2 t ha^{-1} or more (Trébuil et al 1984). Table 4 shows that, if average yields for DSR and TPR were 1.7 and 2.2 t ha^{-1}, respectively, interfield variations in RLR yields were important in both cases. Diagnostic agronomic studies conducted to explain this variability in RLR yields in farmers' fields found that land preparation and poor crop establishment, water depth, weed competition, particularly by wild rice, and damage caused by rats and crabs in densely planted fields with early maturing cultivars were major factors limiting RLR productivity (Crozar and Chitapong 1988).

Table 4. Comparison of crop and labor productivity in rainfed lowland rice between the main crop establishment techniques in medium paddies of Sathing Phra, southern Thailand, 1982-83 wet season.

Crop establishment technique	Yield (t ha^{-1})			Person-d ha^{-1}			Kg paddy person-d^{-1}		
	Min.	Max.	Av	Min.	Max.	Av	Min.	Max.	Av
Dry-seeded rice	0.5	3.0	1.7	8	220	107	7	40	21
Wet-seeded rice	2.4	2.9	2.6	98	150	124	16	25	21
Transplanted rice	0.9	4.2	2.2	45	161	97	8	47	24

Labor productivity analysis

Depending on the type of farming system, the total amount of time spent in RLR fields varies. Type I farms invest from 62 to 94 person-d ha^{-1}, with women exclusively in charge of transplanting, thinning-seedling redistribution, and harvesting, while men give priority to off-farm employment. A similar amount of person-d ha^{-1} is observed on type III farms, but here the labor force works in many more fields and on a larger planted area. With few other employment opportunities during the rice crop cycle, type II farmers invest from 94 to 140 person-d ha^{-1} in their RLR fields. They aim to maximize the productivity of family labor through allocation among different blocks of paddy fields.

During the 1980s, the levels of gross labor productivity in rice for each of the three types of farming systems were 19–24, 13–15, and 20–30 kg paddy d^{-1} for types I, II, and III, respectively (Trébuil 1987). If only family labor is taken into consideration, these numbers change to 29–95, 13–16, and 26–88 kg paddy per d^{-1} for types I, II, and III, respectively, displaying a greater difference between household categories, while displaying similar between-field ranges of variation in performance. Table 4 shows that the average gross labor productivity was somewhat lower in DSR than in TPR, but this difference was not statistically significant. This was because of the large amount of time spent in hand weeding–thinning–seedling redistribution in DSR. This is also associated with a more frequent harvesting of RLR panicle by panicle, using the traditional digital blade called *kae* in broadcast DSR fields where maturity is more heterogeneous. From zero up to 100 person-d ha^{-1}, it was also found that each additional hand-weeding day increases RLR paddy yield by 72 kg ha^{-1}. This illustrates the important yield-depressing effect of weed competition in local DSR paddy fields.

Farmers' integrated approach to controlling wild rice

Following many decades of RLR cultivation with DSR as the main crop establishment technique, among the different types of weeds found in Sathing Phra paddies, wild rice is the most dreaded by farmers (Trébuil et al 1984). Up to more than 100 wild rice seedlings m^{-2} are observed in some fields a few weeks after sowing. Natural crosses by which the wild rice phenotype becomes closer to that of cultivated RLR varieties also make wild rice more and more difficult to control. Because no adapted chemical control method is available, farmers have adopted an integrated control approach, which is mainly based on a sequence of time-consuming cultivation practices.

Farmers assess the extent of wild rice infestation during the fallow period, at the very beginning of the rainy season, by looking for "red rice" grains on the ground. If infestation is high, TPR will be grown. Many times, sequential tillage operations are used to try to produce clean seedbeds. If, after emergence of DSR seedlings, wild rice infestation is high, the young crop is plowed under and the plot prepared again and wet-seeded or transplanted. RLR varieties with specific morphological characteristics (shape and color of leaf, pattern of spatial distribution of tillers, etc.) are chosen to provide a distinction between wild and cultivated rice to facilitate hand weeding. For the past 5 years, farmers also tended to grow more early maturing varieties, which are harvested before wild rice grains mature and shatter on the ground. In dry-seeded fields, farmers prepare relatively coarse seedbed structures with an average clod size of 10-cm diam. Cultivated RLR seedlings emerge faster between these clods whereas seedlings germinating on clods that tend to emerge later are all wild rice and are more easily identified and hand-weeded. Seeds for future cropping seasons are selected by harvesting panicles one by one using the traditional *kae*. When hand weeding has to be stopped when fields are permanently flooded, wild rice plants are cut by a sickle before they flower and are used to feed cattle in December and January. Later, as heading of wild rice usually occurs before that of local cultivars, wild rice panicles are cut by using the *kae* to limit further infestation.

Generally, not all of these practices can be carried out in infested fields during the same season and very often wild rice infestation is poorly controlled because of the lack of labor. Effective hand weeding in wild rice-infested DSR fields by using the earlier techniques mentioned required 150 person-d ha^{-1}. This also explains why, as labor availability is decreasing, farmers have recently increased the use of wet seeding to establish their crops and control wild rice better.

Potential of row seeding to improve crop establishment and weed control

During the 1987-88 wet season, a series of on-farm experiments on land preparation and row-seeding were carried out to improve weed control, emphasizing wild rice, and to increase labor productivity in RLR (Moreau et al 1988). An IRRI-designed two-row seeder pulled by a hand-tractor was tested to establish a homogeneous plant stand and to facilitate interrow weeding. Wild rice germinating mainly between seeded rows could then be more easily weeded out. About 40% of the total farmers in the area could be interested in this new RLR establishment technique. They belong to farm types II and III, in which RLR is the major activity and where farmers are interested in increasing their net benefits through improved labor productivity. Most of the time, these farmers own a hand-tractor or can easily hire one in the village.

The use of the seeder is not compatible with late tillage of very wet soil and requires more than one plowing on heavy soils to obtain a seedbed with suitable clod sizes for good rice seed distribution. A finer seedbed was obtained by the hand-tractor pulling the row-seeder as the caged wheels helped produce smaller clods in the soil bands where seeds were deposited. Table 5 shows the relationship between seedbed type at sowing and RLR density at emergence. The rate of RLR emergence was higher and more stable in RS (70–100% emergence, with 30–80 seeds distributed m^{-2} depending on seeder spouts as some broken seeds were found) than in BC (10–70% emergence on bigger clods). Potentially, the seeder allows significant savings in the number of seeds needed to establish the RLR crop since additional seedlings are not needed to maintain plant density in fields affected by early vegetative drought.

The efficient use of the row-seeder implies a soil moisture level at sowing that does not allow the clayey soil to stick to the seed distribution system. Experiments showed that the number of “available days” (i.e., days with suitable soil moisture conditions) usually exceeds the number of “necessary days” (days needed to implement the technique in the whole area where it is planned to be used: 1 d ha^{-1} after two plowings by hand-tractor) until early October only (Fig. 3). This constraint limits the possibility for collective ownership of the seeder by several farmers. No thinning-transplanting was

Table 5. Relationship between type of seedbed structure and rainfed lowland rice plant density at emergence in seven farmers' fields on very clayey soils of Sathing Phra, southern Thailand, 1987-88 wet season.

Item	Seedbed structure						
	Coarse	Medium	Medium	Medium	Fine	Fine[a]	Fine[a]
Plant density m^{-2}	81 a	93 ab	132 b	134 b	186 c	238 d	267 d

[a]There may have been some confusion between cultivated and wild rice seedlings in these two infested fields. Numbers followed by the same letter are not statistically significantly different at 5% according to least significant difference criteria.

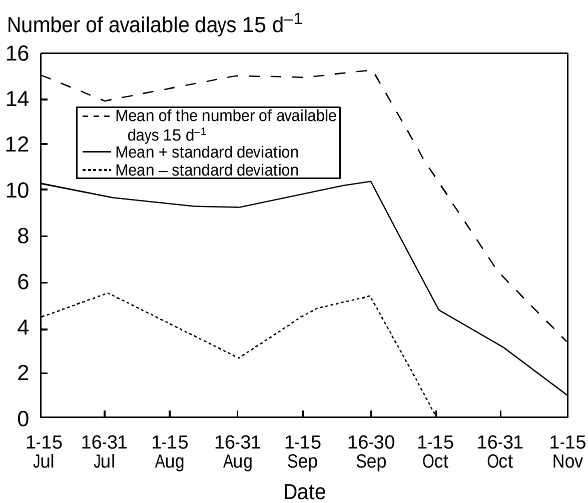

Fig. 3. Analysis of available days for row seeding during 1982-87 in Sathing Phra, southern Thailand.

needed in RS plots in 1987-88 and hand weeding was observed to be twice as long in BC plots than in RS plots with similar weed infestations. This observation was confirmed during similar on-farm experiments carried out the next year in neighboring Phatthalung Province.

Table 6 shows the results of the partial budget analysis for the six collaborative farmers who took part in the row-seeder experiment in the 1987-88 WS. Varying agronomic and economic results were observed in farmers' fields, presenting a gradient in weed infestation. For three farmers' fields with little weed competition, the marginal rate of return (MRR) was negative because in this situation row seeding was a "dominated" treatment (i.e., having a lower net benefit and higher costs that vary). For farmer 3, an MRR of 11% can be considered very low compared with the local cost of investment capital, which can be as high as 120% per year. The very high MRR observed for farmer 2 was due to an exceptionally high RLR yield. Farmer 1 corresponds to a situation in which weed competition was severe, forcing the family to spend 200 and 88 person-d ha^{-1} for hand weeding in broadcast and row-seeded plots, respectively. In this situation, the positive effect of the row-seeder on weeding time and labor productivity is highlighted. The use of the seeder resulted in a 20% increase in labor productivity.

Based on experimental results, the demand for the row-seeder under favorable cropping situations was assessed. For the seeder to be an economically attractive option that decreases varying costs and provides higher labor productivity, a farmer sowing a maximum of 1.6 ha of RLR using this machine usually has to spend more than 38 person-d ha^{-1} in hand weeding and 50 d ha^{-1} for 0.8 ha only. The need for the row-seeder under favorable situations could be estimated by looking at weeding-time data collected in many fields over 2 years (Table 3). Two-thirds (in 1982-83 WS) and 85% (in 1984-85 WS) of the fields showed an advantage in using the row-seeder if it could be used to establish 1.6 ha of RLR per farm, and between half (in 1982-83 WS) and more than two-thirds (in 1984-85 WS) of fields could be considered as having favorable situations if only 0.8 ha of RLR per farm were to be row-seeded. This shows that the row-seeder is potentially an appropriate technique for farm types II and III facing acute weed infestations in their RLR fields as it can significantly help achieve economic objectives by increasing both net benefit per land unit and family labor productivity in a majority of field situations.

Nevertheless, many obstacles to the adoption of this technology remain in the Sathing Phra area because of climatic conditions and the need to use the seeder before early October. This is becoming more and more difficult as farmers are adopting early maturing varieties for planting in September-October. This obstacle to adoption can be even more important for farmers depending on contractors for land preparation and row seeding. Poor water control in RLR also results in plant losses from submergence, which are difficult to forecast. This limits interest in the seeder for establishing a target RLR stand at emergence. The spread of the seeder is also limited because of its heavy weight, leading to difficulties in moving it across bunds. Across the lagoon, in Phatthalung Province, where similar trials were conducted during the 1988-89 WS, mainly RLR growers rearing many cattle became interested in the seeder because the

Table 6. Partial budget analysis comparing rainfed lowland rice broadcasting (BC) and row seeding (RS) on six farms in Sathing Phra, southern Thailand, 1987-88 wet season.

Farmer	1		2		3		4		5		6		Pooled data	
Treatment	BC	RS	BC	RS	BC	RS	BC	RS	BC	RS	BC	RS	BC	RS
Yield (t ha^{-1})	2.2	2.0	3.4	4.7	1.9	2.3	2.6	2.6	1.9	1.2	3.3	2.3	2.6	2.5
Net yield (t ha^{-1})[a]	2.0	1.8	2.9	4.0	1.7	2.0	2.3	2.4	1.8	1.1	3.0	2.1	2.3	2.2
Gross benefit (US$ ha^{-1})	206	185	398	548	206	244	151	153	163	101	356	249	246	246
Costs	146	99	38	64	21	55	101	115	73	91	10	26	65	75
Land preparation	–	–	–	–	–	–	24	26	–	–	–	–	4	5
Seeds	4	3	8	6	9	8	–	–	10	6	4	1	6	4
Sowing	1	10	0.3	18	2	22	0.3	16	1	14	0.5	18	1	16
Hand weeding	80	35	30	40	10	25	30	10	12	24	5	7	28	24
Fertilizers	61	51	–	–	–	–	47	63	50	47	–	–	26	26
Net benefit[b]	60	86	360	484	185	189	50	38 D	90	10 D	346	223 D	181	171 D
Marginal rate of return (%)[c]	Neg.	471	11	Neg.	Neg.	Neg.	Neg.							

[a]Net yield = gross yield – losses (at harvest, storage). [b]Net benefit = gross field benefit – total costs that vary. [c]Marginal rate of return = increment in net benefit divided by increment in costs that vary. D = dominated treatment (lower net benefit and higher costs that vary). Neg. = negative.

twice as fast "weeding" time in row-seeded plots allowed them to rapidly collect enough grass to feed their animals during the wet season. This observation emphasizes the need for a whole-farm systems approach when evaluating the suitability of innovations among different smallholders.

Pattern of changes in crop establishment practices and key research issues

Recent changes in RLR crop establishment practices in this area could be seen as a farmers' response to a key constraint, the decrease in availability of farm labor because of more off-farm employment opportunities during the decade of rapid growth (1986-96), and to a new opportunity to improve water control in medium paddies. For the past 10 years, many farms (up to 50% in some villages) have established a 0.2–0.5-ha plot managed under the so-called integrated farming system. This system is based on a pond surrounded by levees where vegetables and fruit are grown. Apart from fish rearing, water from the pond can be used to provide some supplementary irrigation to neighboring RLR paddies. Several canals have also been dug along the drainage channel; thus, water can be pumped into paddy fields when needed. Farmers would like to increase the network of small secondary canals to allow more paddy fields to have access to supplementary irrigation from these canals. At the same time, the submergence-prone lower paddies, where no improvement in water control occurred, tend to be abandoned or are converted into integrated-farming-systems plots.

The more extensive adoption of early maturing recommended cultivars has recently led to the postponement of sowing dates and this facilitates wet seeding in September-October, especially in paddy fields located along the canals providing supplementary irrigation water. WSR is now increasingly used for RLR establishment. WSR was grown on 50% of the total RLR area during the 1999-2000 crop year, up from only 5% in the early 1980s. In the 1999-2000 WS, DSR and TPR were practiced on 40% and 10% of the remaining RLR paddies, respectively, down from 75% and 20% in the early 1980s, respectively. For the past 5 years, this change occurred parallel with the increased adoption of a new set of early maturing (Khao Dok Mali 105, Khao Hom Suphan, and Khao Klong Luang 1; 120 d) and medium-maturing (Khao Chiang, 150 d) recommended varieties, which covered half of the RLR growing area during the 1999-2000 crop year, compared with only 9% planted to similar types of varieties in the early 1980s. Although farmers are interested in their higher yield potentials and long grains that fetch a better market price, they need to grow them under wet-seeding conditions because they are less tolerant of weed competition than local cultivars. WSR is also becoming more popular because, as off-farm employment opportunities are increasing, less labor is available for transplanting or hand weeding in DSR, and the cost of hired labor for such farm work has doubled from US$1.50 to $3.00 d^{-1} during the past 15 years.

More attention could now be directed to improving the leveling of paddy fields to enhance WSR establishment. Research on plot leveling also has implications for land preparation, weed (wild rice) control, water savings, and mineral fertilization. Although 40% of the RLR area is still planted to DSR because water control has not yet been improved, the design of adapted time-efficient integrated methods for wild rice control remains the main research priority.

Conclusions

Recent important changes in farmers' crop establishment practices in the Sathing Phra area emphasized the importance of improvements in water control, with other strategies such as diversification of production and other economic activities to help mitigate climatic and economic risks in RLR-based farming systems. If efforts in that direction are sustained, WSR will likely continue to replace DSR and TPR in this more and more favorable RLR growing area in the future.

This case study has also demonstrated the importance of improving labor productivity in RLR as we are dealing with small farmers who are well integrated into the market economy and for whom the opportunity cost of labor is increasing. Consequently, this criterion should be very high on the list of indicators for assessing and evaluating new technologies in RLR production. At the same time, the experience of improving traditional RLR systems in Sathing Phra has highlighted the relevance of the whole-cropping-systems approach and farming systems approach for designing, testing, and evaluating technical innovations, such as crop establishment practices, with farmers.

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Development trends and farmers' benefits in the adoption of wet-seeded rice in Thailand

S. Isvilanonda

Rice is an important crop in Thailand. A large area and a relatively low production cost have contributed to the country's comparative advantage in the world rice market. Significant investments in agricultural infrastructure, particularly irrigation systems and a marketing network, and in agricultural research and extension over the past few decades are the major factors that have stimulated productivity increases. The widespread adoption of modern varieties and high intensity of rice cropping, especially under favorable production environments, coupled with rapid growth in the nonagricultural sector raised rural wage rates. As a result, opportunities for saving labor in rice production were increasingly sought. This economic necessity led to a shift from the traditional transplanting method of rice establishment to direct seeding using pregerminated seeds. This method is now widely used in the Central Plain of Thailand. This paper analyzes the factors contributing to a successful transition in crop establishment methods and the impact of this transition on factor use and rice profitability on irrigated rice farms.

Rice farming in Thailand has changed in many ways in recent years. The wide adoption of modern rice technology, particularly in irrigated areas, has improved yield and increased cropping intensity. Increasing land-use intensity resulted in a shortage of grazing land and higher cost of animal care for land preparation, which in turn stimulated farmers to substitute power tillers for animal draft power. The adoption of the power tiller, on the other hand, directly reduced the time for land preparation, which in turn reduced the duration of the rice crop cycle. Furthermore, the rapid growth of the nonagricultural sector in the same period stimulated the outmigration of farm labor to cities, which created a labor shortage in rural areas. The shortage of farm labor supply in irrigated areas, particularly in the peak season, and the rise in wage rate significantly affected farming activities, particularly during transplanting and harvesting. The longer time needed to complete the crop cycle of transplanted rice was a constraint to raising rice cropping intensity and farmers' incomes. At the same time, a higher wage rate raised production costs and diminished farm profits. To avoid these problems and to save labor, a wet-seeded (WSR) method was introduced. This paper discusses regional differences in the adoption of the WSR method and its impact on yield, cost, and net returns.

The paper provides background information on rice production environments and trends in WSR adoption, evaluates economic benefits to farmers, and discusses future trends in the adoption of WSR. Conclusions are presented in the final section.

Geographical differences and trends in the adoption of WSR

Geographical differences in rice production areas

Thailand can be divided into three broad regions—northern, northeastern, and central. Rice is an important crop in all these regions. The largest rice area is in the northeast. Poor soil fertility and an erratic rainfall pattern that causes droughts and floods, often in the same season, have kept rice yield in this region low. Glutinous rice is popular in the upper northeast. Soil characteristics in the lower northeast are more suitable for high-quality "jasmine rice."

The northern region has much better soil fertility and water control, but there are differences between the upper and lower northern regions. The upper northern region is a mountainous area with interspersed valleys. Many traditional irrigation schemes facilitate a high intensity of land use in this subregion. Glutinous rice is mostly grown in the wet season, whereas nonglutinous rice is common during the dry season. The lower northern region is an extension of the Central Plain and generally has fertile soils with good water control. Modern rice varieties are widely adopted in this subregion.

The rice bowl of the country is the Central Plain, where commercial rice production is mostly concentrated. The larger share of irrigated area and better access to the wholesale rice market in Bangkok have led to the rapid spread of modern rice technology in this region. However, some flat lowland areas in the region experience deep flooding for several months in the wet season. Deepwater rice or floating rice is commonly grown in this flood-affected area.

Development trend in the adoption of the WSR method

Before the introduction of WSR in the late 1960s, transplanting rice (TPR) was the traditional method of crop establishment in Thailand. It was commonly practiced in irrigated and rainfed lowland rice areas where the water level in the field could be partly managed. Dry seeding of rice (DSR) or the broadcasting method was practiced mostly in deepwater rice areas where water depth was high and uncontrollable, and in rainfed drought-prone areas where rains were uncertain.

As a result of agricultural development during the 1960s, modern varieties (MVs) were introduced in irrigated areas of the Central Plain (Sriswasdilek et al 1975). Generally, nonphotoperiod-sensitive MVs are better suited to irrigated areas. The adoption of these MVs improved yield and rice-cropping intensity, which in turn increased net farm income. As a consequence, farm labor demand in irrigated areas increased dramatically. A relative scarcity of farm labor supply, especially during the peak season, raised the wage rate in irrigated areas (Isvilanonda and Wattanutchariya 1994).

The WSR method was first practiced by farmers in Bangkla District, Chacjoengsoa Province, east of the Central Plain, long before it was introduced in irrigated areas of Suphan Buri Province. In 1984, the planted rice area under this method expanded rapidly to 80,000 ha in the wet season and to 96,000 ha in the dry season (Isvilanonda 1990). The advantage of this method over TPR was reportedly reduced time for seedbed preparation and shortened crop duration in the field by approximately 10 days. This resulted in an increase in rice-cropping intensity from two crops a year to five crops in two years.

A survey of farmers in the 1986-87 wet season throughout the country (Sangplung et al 1988) found that the major method for crop establishment among farmers in all regions was TPR. The dominant method in the northeast region was TPR, whereas, in the Central Plain, this method covered a relatively small area. The adoption of WSR was highest in the western Central Plain (37%) and lowest in the northeast (< 1%). In northern Thailand, the WSR method covered only 3% of the area (Table 1). The spread of the WSR method in the Central Plain was associated with the adoption of MVs.

It seems that, during the 1980s, the spread of WSR was confined mainly to irrigated areas of the Central Plain where MVs had been widely adopted. The adoption of this method in other regions was nil, but, in the Central Plain, it had been adopted in more than 70% of the irrigated areas by 1987. In irrigated areas of the northeast and north, this method covered less than 5% (Table 2). Moreover, DSR was largely observed in flood-prone and rainfed areas of the Central Plain (Isvilanonda and Wattanutchariya 1990).

The change from TPR to WSR in irrigated areas of the Central Plain was nearly completed by the mid-1990s. In the northeast, adoption of WSR in irrigated areas increased slightly (Isvilanonda and Hossain 1998). In recent years, adoption of WSR has increased dramatically in many flood-prone areas of the Central Plain that previ-

Table 1. Farmer adoption (%) of crop establishment methods in the 1986-87 wet season.

Methods of crop establishment	North	Northeast	Central Plain			South
			West	Center	East	
Transplanted rice	85	98	46	35	72	88
Dry-seeded rice	12	2	23	36	15	10
Wet-seeded rice	3	0	31	29	13	2
Adoption of modern varieties	16	8	33	28	21	9

Source: Sangplung et al (1988).

Table 2. Adoption trend (%) in crop establishment method, Thailand, 1987-88 and 1997-98 crop years.

Season and method[a]	Central Plain			North		Northeast	
	Irrigated	Rainfed	Flood-prone	Irrigated	Rainfed	Irrigated	Rainfed
1987-88 wet season[b]							
TPR method	30	35	0	100	100	95	100
DSR method	0	65	100	0	0	0	0
WSR method	70	0	0	0	0	5	0
1997-98 wet season[c]							
TPR method	0	14	0	70	33	77	14
DSR method	0	86	0	0	0	0	86
WSR method	100	0	100	30	67	23	0

[a]TPR = transplanted rice, DSR = dry-seeded rice, WSR = wet-seeded rice. [b]Isvilanonda and Wattanutchariya (1990). [c]Isvilanonda and Hossain (1999).

ously used DSR. A shift in the rice crop calendar[1] coupled with the adoption of MVs and a long-term decrease in field water depth during the wet season are the major factors that led to changes in rice crop establishment methods in these areas (Molle et al 1999).

By the 1998 wet season, adoption of WSR in irrigated areas of the Central Plain was nearly complete. In the north, WSR covered substantial areas in both irrigated and rainfed environments (about 30% of irrigated areas and 67% of rainfed areas). In the northeast, WSR was used in the wet season in about 25% of the irrigated area (Table 2). Its adoption in irrigated areas of Khon Kaen during the dry season reportedly increased afterwards (Isvilanonda and Ahmed 1998). This method is not used in rainfed areas where DSR is the major method of rice establishment.

Farm-level impact of the WSR method

Data and method

To compare changes in factor uses, production costs, and net returns between WSR and TPR, this section used two different data sets of rice farms. The first data set was collected in 1984-85 in an irrigated area of Suphan Buri Province, Central Plain. This data set contained detailed information on different crop establishment methods and production costs. The other set was collected in 1997-98 in irrigated areas of Khon Kaen Province in the northeastern region. Table 3 compares factor uses in rice production and other details about the samples and data sets.

Changes in factor uses. Technology adoption can induce changes in farm resource allocation by altering the marginal productivity of different resources. Compared with the TPR method, in the WSR method, farmers use higher quantities of seeds and herbicides but less labor, particularly for crop establishment. A survey of

[1]Instead of planting rice in June or July before the fields are flooded, farmers in many flood-prone areas now wait until the water level declines in December or January to plant modern rice varieties.

Table 3. Comparison of factor use between wet-seeded rice (WSR) and traditional transplanted rice (TPR) farmers in crop year 1984-85, wet and dry season, Suphan Buri Province, and in 1998 dry season, Khon Kaen Province.

Item	Suphan Buri[a] (1984-85 crop year)			Khon Kaen[b] (1998 dry season)		
	WSR	TPR	% difference between WSR and TPR	WSR	TPR	% difference between WSR and TPR
Samples	83	68		28	2	
Seed used (kg ha^{-1})						
Wet season	129	118	+9			
Dry season	135	118	+14	138	100	+38
Herbicide and pesticide applied (US$ ha^{-1})						
Wet season	8.50	6.40	+33			
Dry season	8.90	6.60	+35	2.00	1.00	+100
Fertilizer applied (kg ha^{-1})						
Wet season	266	266	–			
Dry season	292	261	+12	180	174	+3
Total labor used (person-hours ha^{-1})						
Wet season	288	365	–21			
Dry season	308	388	–21	236	315	-25
Labor use in land and seedbed preparation (person-hours ha^{-1})						
Wet season	43	58	–26			
Dry season	45	57	–21	26	31	–16
Labor use in crop establishment (person-hours ha^{-1})						
Wet season	10	91	–89			
Dry season	9	92	–90	12	123	-90
Labor use in other activities[c] (person-hours ha^{-1})						
Wet season	235	216	+9			
Dry season	254	239	+6	197	160	+23

Source: [a]Modified from Isvilanonda (1990). [b]Calculated from "Socioeconomic database of rice households." [c]Includes labor in weeding, fertilizer applied, pest control, harvesting, and threshing activities.

farmers in irrigated areas of Suphan Buri in crop year 1984-85 found that farmers using WSR employed 9–14% more seeds than those practicing transplanting (Table 3). Farmers used a higher seeding rate mainly to increase plant density. The adoption of WSR was also associated with an increase in herbicide and pesticide application. The value of chemical inputs applied increased by about 34%. Fertilizer use in the wet season was not higher, but it increased by about 12% in the dry season relative to transplanted rice. In contrast, the amount of farm labor use on WSR farms declined by 21% in both the wet and dry seasons. Reduced labor use under WSR relative to TPR resulted mainly from land preparation and seedbed and planting activities. Nonetheless, the adoption of WSR increased labor use for other activities, particularly for harvesting.

Similarly, a farm survey in irrigated areas of Khon Kaen Province in the 1998 dry season also indicated that farmers who adopted WSR increased the quantities of seeds, herbicides, pesticides, and chemical fertilizers that they used. As expected, labor use declined. The adoption of WSR in the wet season, however, was very limited in the surveyed villages.

Changes in production costs. The impact of the shift to WSR on changes in inputs generated a change in production costs. The cost of material inputs increased, whereas that of labor decreased as a result. In crop year 1984-85, costs of seed and chemical inputs increased by 23% in the wet season and by 17% in the dry season. Labor cost, however, declined by 27% in the wet season and by 29% in the dry season. Overall, the net effect was a 2–6% reduction in production costs (Tables 4 and 5).

Changes in yield and net return. The effects of WSR on yield and net return per unit area are shown in Table 6. In crop year 1984-85, WSR resulted in a yield increase of 8% in the wet season and 5% in the dry season. Consequently, net returns increased by 39% and 37% in the wet and dry seasons, respectively.

Table 4. Comparison of production costs between wet-seeded rice (WSR) and traditional transplanted rice (TPR) in wet and dry seasons, 1984-85 crop year, Suphan Buri Province.

Item	WSR method (US\$ ha^{-1})	TPR method (US\$ ha^{-1})	% change in cost of WSR relative to TPR
Wet season			
Cost of seed and chemical inputs	52.80	43.00	+23
Seed	13.60	9.80	+39
Pesticide and insecticide	5.00	3.80	+32
Herbicide	3.60	2.60	+39
Fertilizer	30.60	26.80	+14
Labor costs	52.30	71.90	–27
Hired labor	23.70	31.10	–24
Family labor	28.60	40.80	–30
Hiring power tiller	1.30	1.90	–31
Total variable cost	106.40	116.80	–9
Total fixed cost[a]	66.40	59.90	+11
Total cost	172.80	176.70	–2
Dry season			
Cost of seed and chemical inputs	54.90	46.90	+17
Seed	12.50	10.90	+14
Pesticide and insecticide	5.30	4.00	+33
Herbicide	3.60	2.60	+39
Fertilizer	33.50	29.40	+14
Labor costs	57.60	81.20	–29
Hired labor	28.30	33.00	–14
Family labor	29.30	48.20	–39
Hiring power tiller	2.10	2.10	–
Total variable cost	114.50	130.10	–12
Total fixed cost[a]	65.50	60.50	+8
Total cost	180.00	190.60	–6

[a]Refers to depreciation cost and opportunity costs of capital and land.
Source: Modified from Isvilanonda (1990).

Table 5. Comparison of production costs between wet-seeded rice (WSR) and traditional transplanted rice (TPR) in 1998 dry season, Khon Kaen Province.

Item	WSR method (US\$ ha^{-1})	TPR method (US\$ ha^{-1})	% change in cost of WSR relative to TPR
Cost of seed and chemical inputs	59.0	51.4	+15
Seed	17.7	12.8	+38
Pesticide and insecticide	0.3	0	+
Herbicide	2.1	0	+
Fertilizer	38.9	38.6	+1
Labor costs	58.9	75.5	–22
Hired labor	16.0	21.4	–25
Family labor	42.9	54.1	–21
Hiring threshing machine	11.5	11.2	+3
Total variable cost	129.6	138.1	–6
Total fixed cost[a]	90.0	96.7	–7
Total cost	219.6	234.8	–7

[a]Refers to depreciation cost and opportunity costs of capital and land.
Source: Calculated from "Socioeconomic database of rice households."

In the northeast, rice yield and the rice price for the 1998 dry season were similar for both methods. Returns, however, increased by 18% because of the lower production costs.

Future trend in WSR adoption

Rice farming in Thailand appears to be in transition in response to economic pressures experienced in rural areas. The increasing importance of the nonagricultural sector, coupled with a simultaneous improvement in the rural economy, has gradually diminished the share of the agricultural sector in Thailand's gross domestic product. As a result, the share of agriculture in household income has also decreased. The share of cash income from nonfarm sources increased dramatically from 45% in 1976 to 63% in 1995 (OAE 1997). From 1987 to 1995, the share of agriculture in farm household income declined from 67% to 32%, whereas the share of nonagricultural income rose significantly from 35% to 65% (Isvilanonda and Hossain 1998). Among nonfarm activities, wages contributed to a large proportion of household income. A higher wage rate in urban areas created a "demand pull" that stimulated migration of farm labor to cities. This led to almost a tripling of wage rates between 1987 and 1997 (Table 7).

Despite high wage rates, the spread of WSR so far is concentrated only in the Central Plain. The adoption of this method in other regions is still limited. This points to the existence of other factors that constrain its spread. These reasons are likely to be biophysical rather than economic as wage rates are more or less equal across regions. In north and northeast Thailand, farmers prefer to grow glutinous rice for home consumption. These traditional high-quality glutinous rice varieties are

Table 6. Comparison of yield, production costs, and net return of wet-seeded rice (WSR) and transplanted rice (TPR) in irrigated areas of Suphan Buri, crop year 1984-85, and in irrigated areas of Khon Kaen, 1998 dry season.

Item	Wet season		Dry season	
	WSR	TPR	WSR	TPR
Suphan Buri, 1984-85 crop year[a]				
Farms (no.)	83	68	83	58
Average farm area (ha)	2.90	3.17	2.76	3.08
Average yield (t ha^{-1})	3.73	3.45	3.82	3.63
Change in yield compared with TPR (%)	+8	–	+5	–
Average paddy price (US$)	71.50	70.80	70.80	71.00
Total variable cost (US$ ha^{-1})	106.40	116.70	114.50	130.10
Total fixed cost (US$ ha^{-1})	66.40	59.90	65.50	60.50
Total cost (US$ ha^{-1})	172.80	176.60	180.00	190.60
Cost per ton of output (US$)	46.40	51.30	47.20	52.70
Gross income (US$ ha^{-1})	266.80	244.20	270.30	257.80
Net return (US$ ha^{-1})	94.00	67.60	90.30	67.20
Change in net return compared with TPR (%)	+39	–	+34	–
Khon Kaen, 1998 dry season[b]				
Farms (no.)	–	–	28	2
Average farm area (ha)	–	–	1.37	0.40
Average yield (t ha^{-1})	–	–	2.33	2.40
Change in yield compared with TPR method (%)	–	–	–3	
Average paddy price (US$)	–	–	100.00	102.60
Total variable cost (US$ ha^{-1})	–	–	129.60	138.10
Total fixed cost (US$ ha^{-1})	–	–	90.00	96.70
Total cost (US$ ha^{-1})	–	–	219.60	234.80
Cost per ton of output (US$)			94.40	98.00
Gross income (US$ ha^{-1})	–	–	233.00	246.20
Net return (US$ ha^{-1})	–	–	13.40	11.40
Change in net return compared with TPR (%)	–	–	+18	

Source: [a]Modified from Isvilanonda (1990). [b]Calculated from "Socioeconomic database of rice households."

Table 7. Daily wage rate in crop establishment and area adoption of wet-seeded rice (WSR) by region in irrigated areas, 1987-88 and 1997-98 wet-season crop.

Item	Central Plain	North	Northeast
Wage rate in (US$ d^{-1})			
Crop establishment			
1987-88	1.10	1.00	0.90
1997-98	3.10	2.90	2.90
% change	+182	+190	+222
Adoption of WSR method in irrigated areas, wet season (%)			
1987-88	70	0	5
1997-98	100	30	23

Source: Data for 1987-88 obtained from Isvilanonda and Watanuchariya (1990). Data for 1997-98 obtained from Isvilanonda and Hossain (1999).

photoperiod-sensitive[2]. Thus, modern varieties in these regions are not well adopted. Farmers who grow local or improved local varieties are unlikely to adopt the WSR method. The future expansion of WSR for the wet-season crop in upper north and northeast Thailand is likely to be slow and conditioned by the availability of better quality improved varieties. In addition, rice is grown in the northeast mainly under rainfed conditions, under which the DSR method may be more appropriate than WSR.

Conclusions

The adoption of the pregerminated direct-seeding method in Thailand has been largely concentrated in irrigated areas, particularly in the Central Plain. DSR adoption resulted in less labor use for crop establishment and reduced variable and total costs per area. It has also increased net returns. The study showed that good water control and wide dissemination of MVs, coupled with a high wage rate in the Central Plain, are among the important physical factors that determine WSR adoption. The slower diffusion of WSR in the upper north and northeast is due mainly to biophysical factors rather than socioeconomic factors.

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[2]Popular glutinous rice varieties grown in the upper north and northeast are RD6 and Noew Sann Patong (NSPT). RD6 is a photoperiod-sensitive variety. In contrast, RD8, which is a non-photoperiod-sensitive variety, is not as popular as RD6 and NSPT because of its poor eating quality.

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Changes in crop establishment methods and constraints to adoption of wet seeding in the Chao Phraya delta, Thailand

F. Molle and C. Chompadist

The rice systems of the Central Plain of Thailand have undergone drastic changes in the last 30 years. Technical change has been driven by a combination of factors including demographic changes, land development and water control, and mechanization. The recent spread of wet direct seeding is put in its historical context and the complementarity between dry and wet seeding, the two currently dominant techniques, is shown to be related to different socioeconomic and hydrologic situations. Some prospects for further technical change are addressed.

At around 1855, the date of the Bowring Treaty between Siam and England, which is taken symbolically as the starting point of the expansion of commercialized rice cultivation in the Chao Phraya delta, the 300,000-ha rice area could be conveniently divided into two categories. The first large area encompassed the flood plain of the Chao Phraya River, in which floating rice was cultivated with the dry-seeding (DSR) technique at least as early as the 17th century (Tachard 1688). A second category constituted deepwater rice cultivated with transplanting (TPR) in various scattered areas of the delta where the control of and access to water was better (land along canals and rivers, mostly in the lower delta, for example, the area of Nakhon Chaisi). Most of the time, this transplanted rice could only be grown if water-lifting devices were available.

Although transplanting was believed to have been the dominant technique in the first 30 years of expansion (Manopimoke 1989), the proportion of the two techniques was not clear until 1900. Around 1890, farmers flocking to the tracts of the newly opened Rangsit area successfully adopted the dry-seeding technique used in the floodplain (Johnston 1975). This less labor-intensive technique allowed settlers to farm larger areas with better productivity and reflected the uncertainty attached to the precariousness of their tenant status. By 1900, DSR was gaining popularity, with slightly less than 50% of the farmers in the Central Plain using it (Stiven 1903).

The further expansion of the land frontier in the delta was mostly achieved with dry seeding by broadcasting but dibbling was also used, especially during the very first years following land clearing (Hanks 1972). In 1922-24, although rice fields already covered 1.5 million ha, broadcast fields accounted for 72% of the rice output (Manopimoke 1989), a percentage confirmed in 1930 by Montri (in Feeny 1982), who estimates the share of DSR at 70% and TPR at 30%. The land/person ratio peaked in the delta around this date (Molle 2000) and the exhaustion of cultivable land began to be felt, prompting farmers to raise land productivity by increasing labor input and shifting to transplanting. Although rice continued to expand in surrounding rainfed terraces and uplands with some slumps after the Great Depression and around World War II, transplanting was gradually adopted in all locations where it could technically be used. In 1963, TPR had been adopted in most of the lower delta and in surrounding terraces, whereas physical constraints limited its use in the upper delta, accounting for 22% of the rice area (Small 1972).

The greater Chao Phraya Irrigation Project was constructed from 1957 to 1962. Although water was formerly mostly provided to rice from "below," by gradual flooding, it was also delivered from "above," through irrigation canals following natural levees. The higher lands of the upper delta shifted from being water-deficient to being irrigated. However, changes in productivity fell short of expectations, prompting worried comments and interrogations from irrigation specialists on the profitability of the investment and on the nature of the constraints encountered (FAO/UNDP 1968).

Double cropping was encouraged with the completion of Bhumipol dam in 1964; a few dry years, however, delayed the opportunity to use the dam and farmers' responsiveness remained low. Cropping area first increased from 5 to 11,000 ha in 1971 in the upper delta; three-fourths of this increase occurred in the Samchuk region because of damage experienced in the 1970 rainy season and because of the dissemination focus of the Suphan Buri rice research station, with two high-yielding varieties (HYVs) released in 1969 (Small 1972). A second increase occurred in 1973, after the beginning of the operation of the Sirikit dam, which notably increased the available water in the dry season (Ngo 1980).

The two dams were expected to provide a yearly release of 5 billion m^3 between January and June, but calculation showed that this available water was not likely to allow the irrigation of more than 25% of the nonflooded part of the upper delta, on around 74,000 ha (in addition to the West Bank in the lower delta) (Small 1972). This pessimistic projection was further compounded by several factors, including the lack of on-farm development, canal design corresponding to full-supply wet-season supplemental irrigation, lack of credit and incentive to improve the land for tenant farmers, and the expected labor shortage at peak periods (Kaida 1978).

Double cropping, however, sharply expanded throughout the 1970s (reaching 217,000 ha in 1979), with an increase in HYV use. Dry-season cropping opportunities and a boom in rice prices in 1973 provided the incentive for its adoption. These changes in cropping intensity, average yields, and farm-gate price, together with other improvements in credit supply and farm mechanization, greatly contributed to easing the deadlock experienced around 1970 and to averting the looming crisis (Molle and Srijantr 1999).

Transplanting expanded further, served by abundant family labor and better water control. From 22% of the upper delta in 1963, its share rose to 45% in 1970 (Manomaiphan 1971), eventually covering all the nonflood-prone areas. The floodplain remained cropped with deepwater (33%) and floating rice (22%) varieties established by dry broadcasting. Figure 1 shows the location of rice areas cropped with TPR and DBR in 1977. The upper delta had widely shifted to TPR but several low-

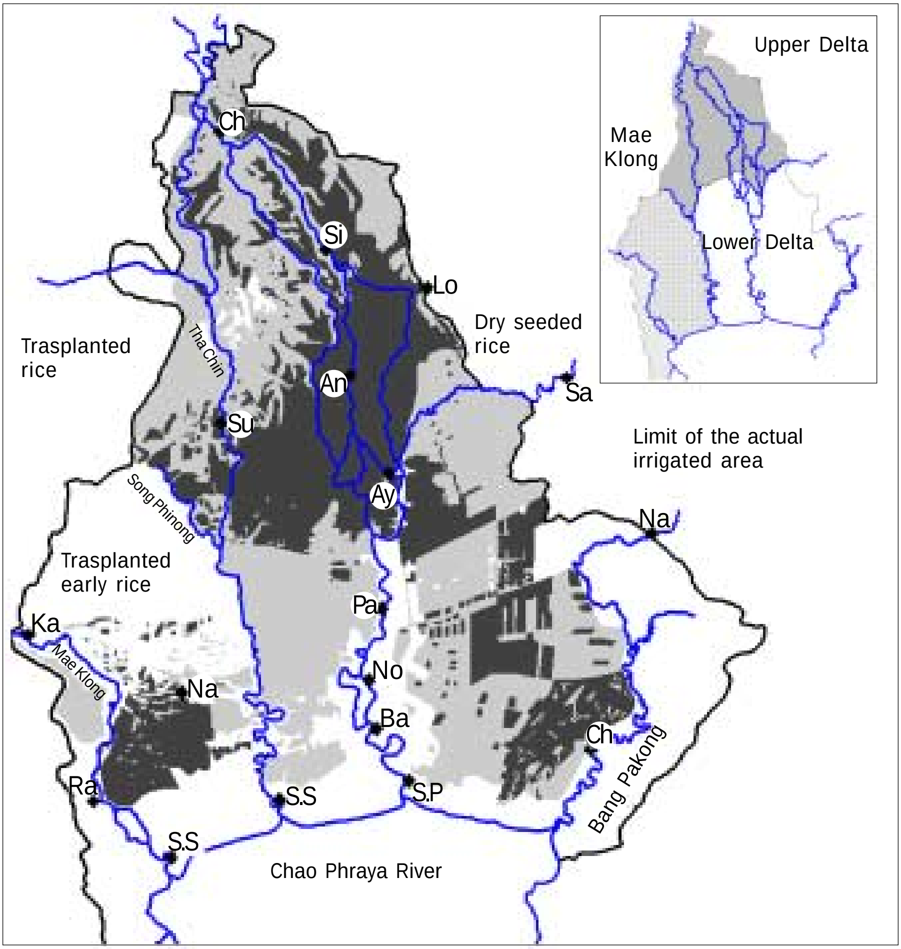


Fig. 1. Rice-cropping area in 1977. (Adapted from ILACO et al 1980.)

From north to south: **Ch** = Chai Nat; Si = Sing Buri; Lo = Lop Buri; An = Ang Thong; Sa = Saraburi; Su = Suphan Buri; Ay = Ayutthaya; Na = Nakhon Nayok; Pa = Pathum Thani; No = Nonthaburi; Ka = Kanchanaburi; Na = Nakhon Pathom; Ba = Bangkok; Ch = Chachoengsao; Ra = Ratchaburi; S.P = Samut Prakan; S.S = Samut Sakorn; S.So = Samut Songkram.

lying areas, together with the bulk of the floodplain, were still under DSR. Significant differences between 1963 and 1977 appeared in the East Bank (east and northeast of Bangkok) (Molle 2000). Although part of the North Rangsit Project has adopted TP, the area along the Bang Pakong River (Chachoengsao Province, southeastern part of the delta) has chosen to (momentarily) revert to DSR. Little information has been found to document this situation; Takaya (1987) mentions (for 1980) that rice is "mostly transplanted, sometimes broadcast."

The map does not wholly encompass the Bang Pakong area (to the east) and the upper Mae Klong project (to the west), mostly planted with sugarcane. For the latter, additional information is provided by the Mae Klong Integrated Rural Development Program (Kasetsart University et al 1978), which confirms that 62% of the area along the Song Phi Nong and Tha Chin rivers had already shifted to TPR in 1976.

The change also affected 33% of the higher terraces (around the *amphoe* Bang Pakong), whereas southern Nakhon Pathom remains under DSR. Eighty-five percent of the right bank of the Mae Klong River, already transplanted in the 1963 census, is under TPR.

The spread of wet seeding

The biggest expansion of TPR in the delta was observed in 1977 (Table 1). This impressive growth, however, was the prelude to an even quicker decline with the advent of direct seeding in the 1980s. Farmers in the Central Plain already practiced direct seeding in muddy conditions. In lower locations where water often impounds year-round or during late sowing when the first runoff already accumulates, farmers resort to seeding in the water or in the mud if pumping out is possible; this technique is called *pholei*. Panichpat (1990) reports that in the early 1970s the idea of adapting sowing with pregerminated seeds to normal conditions was developed. The technique, after a series of experiments, became well known as (*naa wan) nam tom* (NT) and came to be more widely known as wet seeding (WSR). It has been used at least since 1975 around Chachoengsao Province (Inoue and Bhasayavan 1982) and in the upper delta during the dry season (Lokaphadhana 1976).

Further data on rice-cropping techniques incorporate this change: data for 1985 from the Department of Agricultural Extension (DOAE) showed the techniques used by the province (Gallois-Bride 1986). Wet seeding accounted for one-third of the

Table 1. Breakdown of technique used per subregion in 1977.

Area	Direct seeding		Transplanting	
	Area (km^2)	(%)	Area (km^2)	(%)
Upper delta	3,436	48	3,680	52
Lower delta	2,367	35	4,423	65
Mae Klong	828	60	563	40
Total	6,631	43	8,666	57

Source: Molle (2000).

Table 2. Percentage of rice-cropping techniques, by province in 1985 (DOAE[a]).

Province	Technique[b]			
	TPR	DSR	WSR	Total
Ang Thong	77.0	261.7	130.9	469.6
Ayutthaya	323.0	778.1	1118.2	2,219.3
Bangkok	71.0	63.2	138.7	272.9
Chai Nat	448.0	284.2	161.5	893.7
Lop Buri	534.0	392.6	0	926.6
Nonthaburi	14.7	178.4	0.1	193.2
Pathum Thani	0.2	100.3	413.8	514.3
Saraburi	524.0	127.6	1.6	653.2
Sing Buri	60.0	152.3	188.5	400.8
Total	2,051.9	2,338.4	2,153.3	6,543.6
	31%	36%	33%	100%

[a]DOAE = Department of Agricultural Extension. [b]TPR = transplanting, DSR = dry broadcasting, WSR = wet broadcasting.

area, whereas transplanting decreased to 31% and dry seeding made up the remaining 36% (Table 2).

Data for 1992 were provided by the Office of Agricultural Economics (1993) by province: TPR made up only 10% of the area, whereas wet broadcasting increased to 52% and DSR accounted for 37%. By 1998, transplanting had almost totally disappeared (Kasetsart University and ORSTOM 1996, Molle et al 1999). The most recent statistics showed that TPR is practiced only in provinces (Sara Buri, Lop Buri, Suphan Buri) with a large share of nonirrigated rice (OAE 1998). Dry seeding is now mostly confined to the Chao Phraya floodplain, with additional secondary areas in the lower Mae Klong area and the Bang Pakong area.

Figure 2 indicates the area where traditional varieties are used (deepwater and floating rice varieties). It more or less corresponds to the area using DSR, but the equivalence is not total, as will be shown later. Other rice areas (in white) currently use WSR.

Advantages of wet seeding

The surge in WSR raises questions as to what factors spurred its quick adoption. Several studies have shown that WSR promptly gained wide acceptance in areas where it was technically suitable, because it was labor-saving and economically attractive (Lokaphadhana 1976, Isvilanonda and Wattanutchariya 1990, Wongchanapai 1982). As early as 1981, it was supported by the wet-seeded direct-seeding project implemented by DOAE (Gallois-Bride 1986).

The most striking aspect in the adoption of WSR is the context of the labor shortage that built up in the late 1970s. The 1960s were characterized by a “saturation” of the agrarian system, including growing population pressure (Molle 2000). How did such a change occur? First, the 1960s were marked by the removal of a significant part of the delta population, mostly through migration to the newly opened upland frontier and to Bangkok. During this decade, agricultural population in the

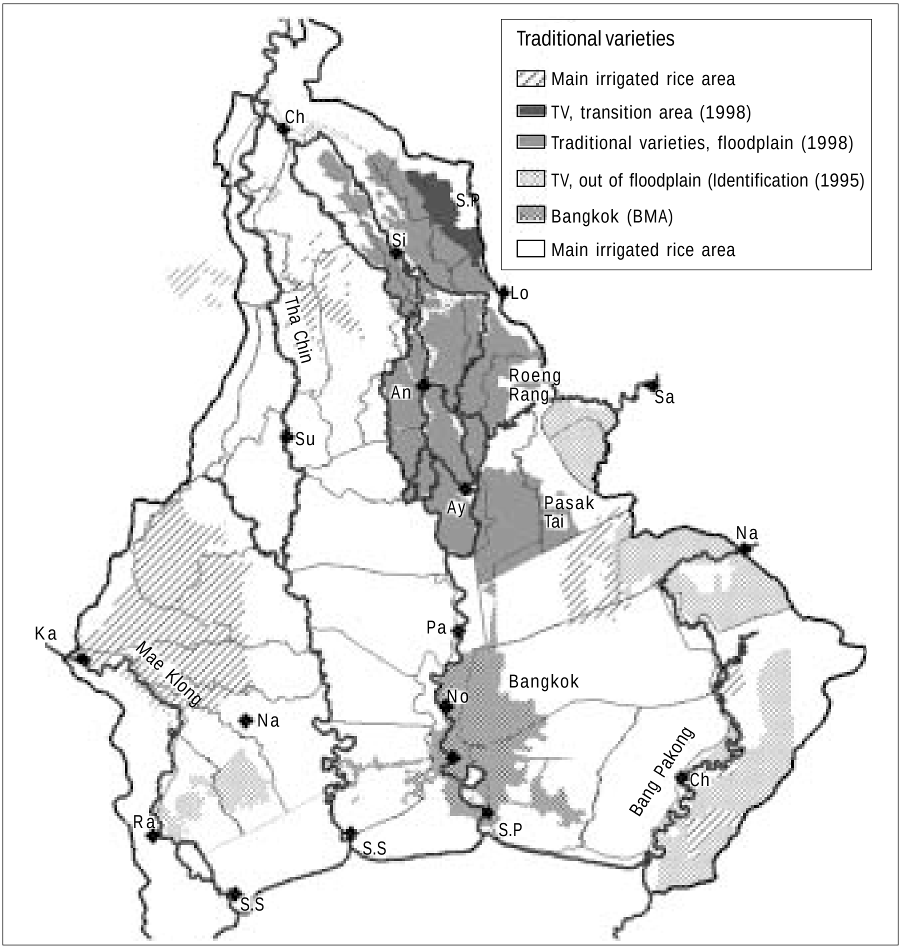


Fig. 2. Extension of traditional varieties in the Chao Phraya delta (1998).

From north to south: **Ch** = Chai Nat; Si = Sing Buri; Lo = Lop Buri; An = Ang Thong; Sa = Saraburi; Su = Suphan Buri; Ay = Ayutthaya; Na = Nakhon Nayok; Pa = Pathum Thani; No = Nonthaburi; Ka = Kanchanaburi; Na = Nakhon Pathom; Ba = Bangkok; Ch = Chachoengsao; Ra = Ratchaburi; S.P = Samut Prakan; S.S = Samut Sakorn; S.So = Samut Songkram.

rural delta decreased. Second, although transplanting in the wet season posed no problems for labor, the advent of double cropping entailed some bottlenecks in farm operations. Although the overall labor supply was still considerable, labor demand peaked a few times because of the expansion of double cropping (Komate 1976).

These shortages were first dealt with by the rapid spread of two-wheel tractors and the concomitant disappearance of buffalo use for land preparation. In addition, these tractors were useful to power low-lift axial pumps, which turned out to be very important for gaining access to water.

In 1980, a labor shortage surfaced as an overall constraint, at least at transplanting time, matching the requirements of cropping calendars as governed by the water regime. Piecework wages increased and finding hired labor became a burden. WSR offered a solution and farmers swiftly resorted to the new technique. The value of an agricultural daily wage index of 100 in 1985 (deflated by the inflation rate) rose to 150 in 1985 and 200 in 1990 (Molle 2000). The surge in WSR in the late 1970s in Chachoengsao Province, southeast of Bangkok, is closely linked to labor shortages and rising real wages (Banpasirichote 1993). With the shift in techniques, labor input decreased by 20% (Isvilanonda, this volume).

The shift was also spurred by the fact that making nurseries for seedlings was constrained by crop care, the need for an earlier and longer water supply, a decrease in flexibility to choose the start of cultivation based on the later effective availability of water, and because farmers were satisfied to do away with nurseries.

On the other hand, the change in technique was cost-effective (Isvilanonda, this volume). With the monetization of labor exchange, transplanting had raised production costs; the change in technique entailed a replacement of labor input (transplanting) by capital input (more herbicide is required to control weeds at crop establishment with WSR), but, on the whole, WSR appeared to be cost-effective, as yields were basically unchanged in the shift (Inoue and Bhasayavan 1982, Isvilanonda and Wattanutchariya 1990, Lokaphadhana 1976).

With this additional advantage of increased economic profitability, there was little scope for farmers to continue transplanting their crops. The new technique, however, required a more careful leveling of the plot, compelling some farmers to invest in plot improvement. Regarding water use, there is no definite consensus on the impact of the shift. Some observers believe that WSR requires more irrigation water than TPR and that it is conducive to "big problems and conflicts in water use, especially during the dry season" (JICA/RID 1989). We tend to believe that the difference is not so significant and that, in any case, shortening the supply period because of the absence of nurseries offsets the increase in water use.[1] The rice cycle (and water requirements) is shortened by using short-cycle (90-d) varieties.

From transplanting to wet seeding: a shift with exceptions

Thus, all transplanted fields have shifted to WSR in little more than a decade. Although this is generally true, there are a few exceptions.

A first category of plots are topographically unfit for WSR; this includes plots with poor leveling and those with poor drainage. In the latter, transplanting may have been chosen to establish rice in ill-drained depressions where water gathers with the first rains and tends to stagnate. In this case, WSR and DSR are not possible unless pumping is used. The development of individual mobile pumping capacity has helped

[1]Water use is believed to increase because of the shorter duration of plot irrigation for transplanted rice and the need to drain water after puddling and before sowing. The first point is debatable because the nursery, although established over a tenth of the plot, also requires longer supplies, with the same conveyance losses. For the second point, water is often reused downstream and is not lost for the system as a whole.

in many cases. Drainage has also been continually upgraded during the last three decades. Transplanting is now exceptional in the delta (no more than 1%) and is mostly limited to specific locations or to families with tiny plots.

A second set of counter-examples is related to the question of reliability and effectiveness in access to water. If we compare the transplanted area in 1977 and the actual area under WSR, some areas have not followed the shift from TPR to WSR and instead have reversed from TPR to DSR! This is particularly the case in the Pasak Tai Project, northwest of Bangkok, in the Roeng Rang Project, and in the transition zone on the eastern part of the delta (Fig. 2).

Two factors mostly govern such a technical choice. The first is the timing of water deliveries: if the large amount of water needed for land preparation cannot be provided satisfactorily or in due time, farmers may prefer crop establishment in rainfed conditions and wait for irrigation water. This suggests that more stress-resistant deepwater varieties must be chosen instead of HYVs. Some farmers may also directly consume the rice they produce, whereas HYVs are all sold and rice for consumption is bought instead, usually at a higher cost. Second, DSR may also be more attractive because of lower land preparation costs. Farmers with no tractors have to pay around two and a half times for land preparation in WSR in comparison with two runs of a four-wheel tractor under dry conditions.

In such a case, the choice between the two techniques depends particularly on the conditions of water supply. This can be observed in the transition zone and along the east bank of the Bang Pakong River.

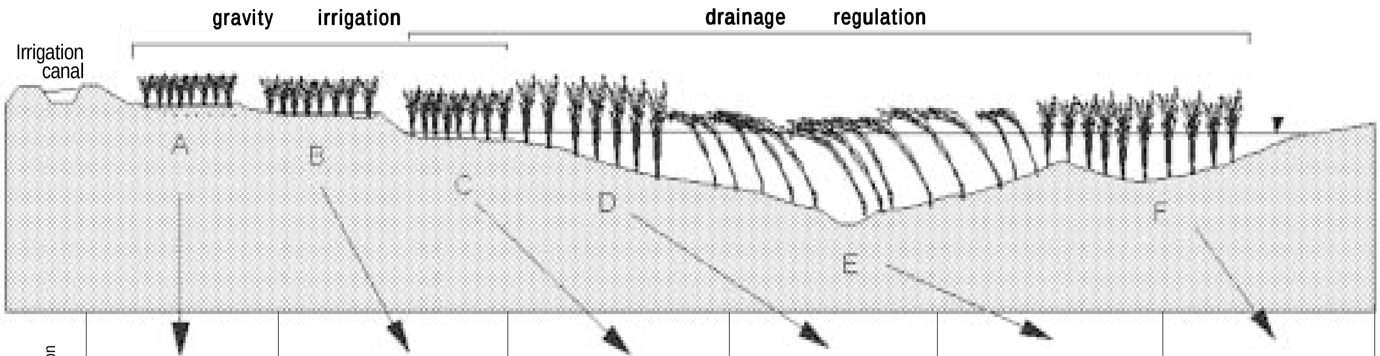
Relationship between dry-season cropping and wet seeding

Technical decisions regarding crop establishment are more complex when we consider the occurrence of double cropping. The clear-cut descriptions above apply to HYVs (simple or double cropping with WSR) and monoculture of traditional varieties (deepwater and floating rice with DSR). These two situations are found at the two extremes of the toposequence (Fig. 3). In the first case (A and B), water is provided by the gravity irrigation network, particularly for land preparation. In the second case (D and E), rice is established in rainfed conditions and is later flooded by the rise in water level obtained by drainage regulation.[2] In the intermediate situation (C), deepwater rice is planted with either the DSR or the WSR technique: if water is allocated for a dry-season crop, an HYV will be grown with WSR. In this case, the ensuing wet-season crop—a deepwater variety—is *also* established with WSR. This is because the plot is already wet, the soil profile is almost saturated, and the water required for land preparation is less[3].

In many instances, too, the dry-season crop is grown very late and there is not enough time to establish a deepwater variety with elongation ability under rainfall

[2]This rise is not due to flooding from the river system, as is commonly believed, but to the regulation of the drainage of inner runoff. For more details, see Molle et al (1999).

[3]We have found an exception to this situation–farmers growing the wet-season crop with DSR after a dry-season crop with WSR–but this is extremely rare.



	A	B	C	D	E	F
Main situtation	High Yield Varieties wet seeding double cropping	High Yield Varieties wet seeding single cropping	Deep water rice wet seeding single cropping	Deep water rice dry seeding	Floating rice dry broadcasting	Deep water rice transplanting
Secondary situtation	Favorable situation for diversification	Traditional varieties with dry seeding if no water for land preparation	Double cropping if enough water or individual water resource	Wet seeding, with pumping water out, if early ponding water		Dry seeding, if no early ponding water
Water and plot conditions	good access to irrigation water; good drainage conditions; good plot conditions	good access to water and good drainage conditions in the rainy season; poor access to water in dry season; good plot conditions	medium access to water; risk of prolonged flood or water depths between 40 and 100 cm; plot bunding and leveling	poor access to irrigation; prolonged flood with depths between 40 and 100 cm; poor or no on farm development; water level regulated in the drain	poor access to irrigation; quick or prolonged flood with depths over 100 cm; poor or no on-farm development; water level regulated in the drain	poor access to irrigation; ponding water after the first rains; bad drainage conditions; plot bunding and medium leveling
Harvest-ing period	(October)/November		December/(January)		January/(February)	December/(January)
Some varieties	Chainat, Suphan 60 KK23, KK35, etc.		khaw ta heng, luang pratiew, khon keew khaaw pakuat, puang thong, khaw jet luang, etc.		khaw lamyaay, pinkew khaw hom thung, etc.	khaw ta heng, khaw luang pratiew, etc.
Socio-economic features	average rice farm: 3.5 ha, agricultural diversification, rice intensification		average rice farm: 4.5 ha (Ayutthaya province), ageing population, rural industries, out-migration			

Fig. 3. Logical framework for the choice of rice type and cultivation technique.

before the water comes. The lower the plot, the higher the risk of it being damaged. This is why some farmers starting a dry-season crop as late as June sometimes prefer giving up the next wet-season crop. Also noteworthy are areas where farmers establish floating rice varieties with wet seeding (after a dry-season crop).

Figure 3 also shows what secondary situations might be observed in each topographical location. In situation B, for example, DSR can be used if irrigation supplies are unreliable (transition zone, see above). These descriptions apply to the flood-prone area of the delta (approximately the gray area of Figure 2. In other areas, irrigation and drainage facilities allow the use of HYVs with single, double, or triple cropping.

Research issues and scope for further technical change

From the technical point of view, the spread of WSR to all areas with good water control may appear as the final outcome of an evolution mostly driven by time and labor-saving considerations. Are further technical changes expected or does this technique already provide a blend of factor uses which is unlikely to be modified in the near future?

Situations A and B. In areas with good water control, further evolution should be driven by the pressure on water resources, as typified by the decline in the amount of water that can be allocated to rice cultivation in the dry season.

This should pave the way for other forms of direct seeding associated with adequate forms of land preparation. A promising technique, observed in a few rare cases, consists of plowing the plot in semidry conditions and sowing dry seeds after flooding and draining the plot. Although weed pressure must be dealt with, this technique allows for a significant reduction in water consumption and should be comprehensively tested in the delta. Another water- and labor-saving technique observed in the Mekong Delta, especially in areas with a rotation of three rice crops per year, is the so-called zero-tillage technique—dry seeds are sown on plots after the stubs of the preceding crop have been burned, but with no land preparation. This technique also reduces labor costs and, although already commonly observed in some parts of the delta (Bang Len District, for example), the conditions of its wider dissemination should be investigated.

The need to decrease production costs is likely to be the second driving force in technical change. This could be attained by better pest and nutrient management and by lower costs in mechanized harvesting as a result of an increasing supply of harvesters, as is currently observed.

Another variant of the direct-seeding technique sometimes observed in the delta is *waan ché*. Pregerminated seeds are sown in a few centimeters of water and the plot is drained after a day. This allows a slightly longer drainage time in some instances. The technique is well adapted to some soil types. After wet seeding, some seeds fall on microelevations of the mud bed, and, in the dry season, are quickly baked by the sun. This may trap some seeds and prevent sprouting, an inconvenience avoided with the *waan ché* technique, which may also provide better weed control.

Situations D and E. In flood-prone areas where dry seeding is used, few technical changes are expected. Techniques are dictated by the hydrological regime, which is unlikely to be altered. On the other hand, land preparation and harvesting are already mechanized. Changes can be expected in limited areas, following a pattern of abandoning flooded rice in favor of one or two postflood high-yielding varieties. This shift, begun 20 years ago in the western part of the lower delta (an evolution related to that of the flood-prone area of the Mekong Delta), recently expanded to other areas, as described in Molle et al (1999).

Conclusions

Wet seeding expanded in the Chao Phraya delta starting in the late 1970s and replaced transplanting in slightly more than a decade. The labor shortage, especially during peak periods, widespread dissemination of herbicide, and cost-effectiveness have spurred its adoption at the expense of TPR. Even under conditions of Asian smallholder agriculture, transplanting, after thousands of years of use, has become a burden. The shift has been observed in many areas in Southeast Asia, such as the Mekong Delta, where the average farm size is much lower than the 4 ha in the Chao Phraya delta.

After the mechanization of threshing and land preparation, and after the demise of transplanting, the remaining and last labor-intensive bottleneck in rice production was harvesting. In the delta, its mechanization began around 1990, starting in areas cropped with HYVs and later spreading into the flood-prone area, with 72% of the latter being harvested mechanically in 1998 (Molle et al 1999). This sequence of drastic cuts in labor requirements now opens the way for an easier management of larger farms with hired labor and mechanization, a possible destabilizing element for smallholder-based agriculture. An embryonic development of such farms (> 20 ha) is observed in the flood-prone area of the delta (Molle and Srijantr 1999).

The spread of WSR should pave the way for other forms of direct seeding aimed at reducing both water use and production costs. These include dry seeding on plots wetted by irrigation, dry seeding associated with zero-tillage techniques, as sometimes used in triple cropping, and developing improved pest and nutrient management.

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Economics of direct seeding in northeast Thailand

S. Pandey, L.E. Velasco, and N. Suphanchaimat

In Thailand, the rice establishment method has shifted from transplanting to direct seeding in response to labor scarcity. Using survey data from Khon Kaen, this paper examines patterns of the shift in crop establishment methods, factors influencing the choice of crop establishment method, and the impact of such a shift on rice production and productivity. Results show that biophysical factors such as weed incidence, rainfall pattern, sufficiency of water supply, field elevation, and hydrology are the major determinants of farmers' choice of crop establishment method. In addition, wage rates, availability of family labor, and power for land preparation were found to be the major economic factors influencing the choice of crop establishment method.

Although rice yields were similar for wet seeding and transplanting, dry seeding resulted in a significantly lower yield. As dry seeding is practiced mainly in upper fields with lower productive capacity, rice production in these fields would not have been economically viable had farmers not used this labor-saving method. A lower technical efficiency associated with dry seeding relative to other methods indicates that potential exists for improving the dry-seeding method through better technology. Implications for developing technologies for land preparation, weed management, developing new varieties, and other aspects of rice production are derived.

One of the obvious changes in Asian rice production during the last decade is the shift in crop establishment method. Thailand is not an exception to this phenomenon. Although transplanting (TPR) remains the most important method of rice establishment, approximately 34% of the 9.6 million ha of rice land in the country is direct-seeded (Pandey and Velasco, this volume). Increasing demand for rice, decreasing water supply, rising labor scarcity, and increasing wage rates are some of the driving forces for this change. During the early 1990s, the rapid shift from transplanting to direct seeding, specifically to dry seeding (DSR), was evident in northeast Thailand, where 5 million ha of rainfed rice is grown (Fig. 1).

Khon Kaen Province of northeast Thailand provides a good example of rice farms integrated with the nonfarm economy. Here, labor was drawn rapidly from the farm to the nonfarm sector during the early 1990s, leaving behind a shortage in agricultural labor. As a result, farmers adopted direct-seeding methods to cope with the labor shortage. Between 1989 and 1996, the dry-seeded area increased from about 5% to almost 60% of the total rice area in Khon Kaen (Fig. 2). Although there are some year-to-year fluctuations in area under direct seeding, the positive trend is clearly evident.

In Khon Kaen, dry seeding and transplanting are the major methods of crop establishment in rainfed areas, whereas, in irrigated areas, farmers use wet seeding and transplanting (Fig. 3). Irrigated rice production in Khon Kaen started in 1972 after the construction of a dam in Nam Pong District to generate hydroelectricity, prevent major floods, and provide water for irrigation. This irrigation system was able to supply water to 7% of the rice area. Wet seeding (WSR) in the dry season was first introduced to farmers in Khon Kaen after this irrigation system was installed. Farmers were encouraged to establish a second rice crop using wet seeding. Based on their experience with wet seeding during the dry season, farmers started to shift from transplanting to wet seeding during the wet season to save on labor and costs.

This study aimed to conduct an economic assessment of direct-seeding practices in Khon Kaen, northeast Thailand. Specifically, it compared the economics of direct-seeding methods with transplanting methods in rainfed and irrigated environments. It also identified factors that determine the adoption of alternative methods of rice establishment.

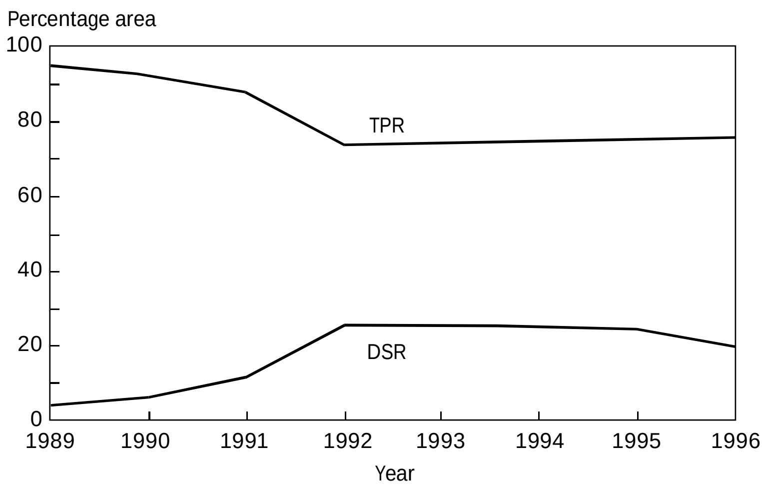

Fig. 1. Trends in adoption of rice establishment method in northeast Thailand by percentage area. TPR = transplanted rice, DSR = dry-seeded rice, WSR = wet-seeded rice.

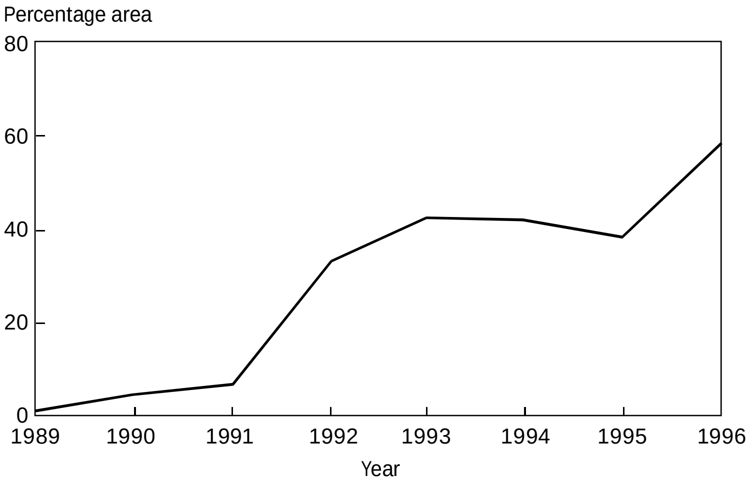

Fig. 2. Trends in adoption of dry-seeded rice in Khon Kaen, Thailand, by area planted.

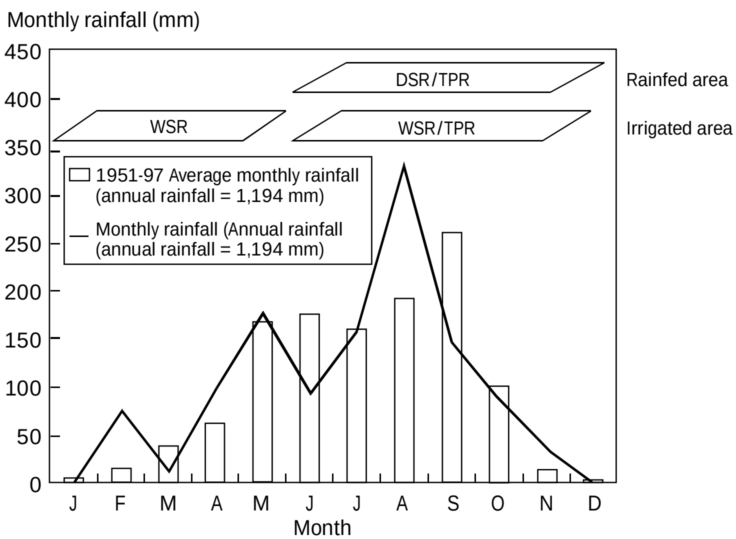

Fig. 3. Rainfall and methods of rice establishment in Khon Kaen, Thailand. WSR = wet-seeded rice, DSR = dry-seeded rice, TPR = transplanted rice.

Data and methods

A survey was conducted in 1999 in Khon Kaen in collaboration with the Department of Agricultural Economics, Faculty of Agriculture of Khon Kaen University. Households were selected using purposive sampling to ensure representation of farmers who adopted direct-seeding methods. Since wet seeding was not commonly practiced in the rainfed area, farmers who dry-seeded or transplanted rice in at least one plot were selected. In the irrigated area, farmers who wet-seeded or transplanted rice in at least one plot were included in the sample since dry seeding is not commonly practiced in this area. Because of the nature of the sampling scheme used, generalizations regarding the extent of adoption of different crop establishment methods in the population cannot be made. The sampling design, however, permits comparison among alternative methods of rice establishment.

Figure 4 shows the location of the survey sites in Khon Kaen. In the rainfed area, the study was done in Nong Rua District, where 112 farmers were interviewed from four selected villages (Table 1). In the irrigated area, 61 farmers were interviewed in two villages of Nam Pong District.

Information on demographics, land inventory, and crops grown was collected for each farm household. Detailed information on input use and costs was collected from the largest plot. Farmers' perceptions on various aspects of alternative methods of rice establishment were also gathered. The economic analysis was based on a comparison of the productivity and profitability of different crop establishment methods, and it identified factors that favor different methods.

Plot-level data were used to identify factors that determine variations in direct-seeding methods across plots and across households. A probit model was estimated for this purpose. The dependent variable is a binary variable that identifies a plot as being direct-seeded or not direct-seeded. Several plot-specific factors and household-specific factors were classified as explanatory variables. The major plot-specific factors considered were field elevation and degree of weed infestation in the past. The major household-specific factors included were labor-land ratio, farmers' age, and whether or not the farmer perceived farming as a major income source.

Field elevation determines field hydrology as low-lying fields generally have more clayey soils and tend to accumulate water relative to upper fields, which have mostly lighter soils that drain relatively easily. Transplanting is more suitable in these lower fields where water accumulation may prevent direct seeding. Past studies have indicated that field elevation is an important determinant of the suitability of a field for direct seeding (Pandey and Velasco 1998). Field elevation was specified as a dummy variable in the estimating model. Similarly, with other things remaining the same, farmers are more likely to transplant rice in fields with a history of high weed infestation since weeds are more easily controlled in transplanted fields than in direct-seeded fields. Perceptions on the weed problem were also specified as a dummy variable.

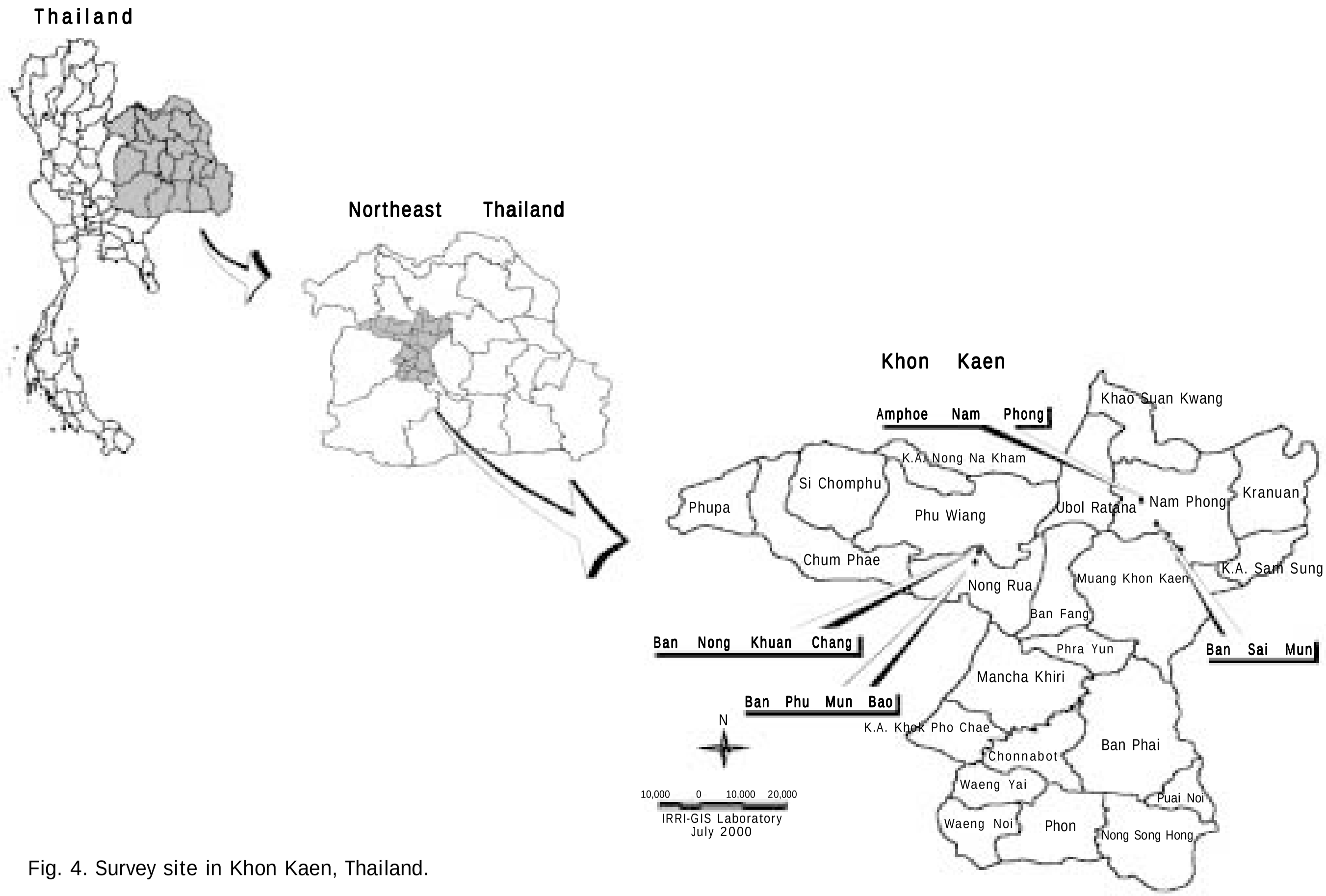

Fig. 4. Survey site in Khon Kaen, Thailand.

Table 1. Number of farmer-participants in the survey in Khon Kaen, Thailand, 1998-99.

Area[a]	Farmers (no.)
Rainfed	
Tambon Non Tong, Amphoe Nong Rua	
Ban Phu Mun Bao	
Mu. 4	33
Mu. 16	20
Ban Nong Khuan Chang	
Mu. 6	37
Mu. 17	22
Total	112
Irrigated	
Tambon Sai Mun, Amphoe Nam Pong	
Ban Sai Mun	
Mu. 1	36
Mu. 2	25
Total	61

[a]Definitions: amphoe = district, tambon = subdistrict, ban = village, mu = administrative no. of the village.

Direct seeding is a labor-saving method and farmers who have more family labor in relation to the land area operated are less likely to direct-seed. Such farmers may prefer transplanting because of the adequacy of family labor for transplanting, which, under farmers' conditions, generally produces a higher average yield. Thus, the coefficient associated with the labor-land ratio in the probit model is expected to be negative. Farmers who do not consider farming as a major source of income are more likely to be interested in increasing their income by participating in nonfarm activities. Such farmers are thus more likely to practice labor-saving direct-seeding methods. Farmers' age may similarly reflect their attitudes toward farming, with younger (and perhaps more educated) farmers being less interested in farm activities. Accordingly, their managerial inputs may be of lower quality. In addition, younger farmers may be less likely to practice the labor-intensive transplanting method. Although income from nonfarm activities may capture some of these effects, age was also included to capture any residual effect.

Production depends on both biophysical and environmental factors and management practices. A production function is used to identify factors that affect yield significantly. However, in addition to identifying factors, production functions can also provide estimates of technical efficiency for each farmer. In simple terms, technical efficiency is measured as the ratio of yield produced by a farmer using a certain level of input to the yield of the "best practice" farmer who uses the same level of input. The production function of the "best practice" farmer is often known as a production frontier since it is an outer envelope of all other production functions. Stochastic production frontiers that account for random variations caused by climatic and other factors are best suited for estimating the technical efficiency of alternative methods of crop establishment. Following Battese and Coelli (1993), the stochastic production frontier is specified as

$$Y_i^* = f(X_{ij})\, e^{v_i - u_i}$$

where
Y_i^* = rice yield of the i^{th} farm,
$f(.)$ = the functional relationship between the dependent and independent variables,
X_{ij} = the value of the j^{th} independent variable for the i^{th} farm,
v_i = the random error that captures the effects of random shocks beyond farmers' control and other measurement errors—it is assumed to be NID$(0,\sigma^2)$, and
u_i = the nonnegative unobservable random variable that represents the inefficiency level—it is assumed to be NID$(E(u_i),\sigma^2)$.

Technical efficiency (TE_i) for the i^{th} farmer is measured as

$$TE_i = \frac{Y_i}{Y_{i^*}} = \frac{f(x)e^{v_i}}{f(x)e^{v_i}e^{-u_i}} = \frac{1}{e^{-u_i}} = e^{u_i}$$

where Y_i is the yield obtained by the i^{th} farmer and Y_i^* is the corresponding yield obtained from the frontier production function. Technical efficiencies for both direct seeding and transplanting methods were estimated using the above formula.

Why do technical efficiencies differ across farms? Variations in technical efficiencies across farms are a function of a range of biophysical and socioeconomic factors. To explain the difference in efficiency among farmers, technical efficiency is assumed to depend on a set of socioeconomic factors and farmer characteristics defined by

$$u_i = \sum_h Z_{ih}\delta_h + w_i$$

where
u_i = technical efficiency parameter for the i^{th} farmer,
Z_{ih} = value of the h^{th} explanatory variable for the i^{th} farmer,
δ_h = parameter to be estimated, and
w_i = unobservable random error, which is assumed to be NID$(0,\sigma^2)$ such that u_i is nonnegative.

As opposed to the usual practice of estimating the frontier production function in the first step and regressing the estimated technical efficiency parameters on socioeconomic variables in the second step, both equations were estimated in a single step. This single-step estimation is more efficient as information about socioeconomic determinants is used in estimating parameters of the production frontier. Estimation was done using the FRONTIER program developed by Coelli (1994).

Table 2. Percentage area planted by sample farmers in Khon Kaen, Thailand, 1998-99.

Crops	Wet season	Dry season	Cropping intensity index
Rainfed area			
Rice	93	0	
Nonrice	7	8	
Total	100	8	1.14
Irrigated area			
Rice	89	52	
Nonrice	11	13	
Total	100	65	1.73
Both			
Rice	92	17	
Nonrice	8	9	
Total	100	26	1.33

Nonrice crops include sugarcane, cassava, groundnut, soybean, maize, tomato, cucumber, vegetables, and pasture.

Results

Methods of rice establishment

The dominant crop grown in Khon Kaen is rice (Table 2). In the rainfed area, rice is grown during the wet season with only a small area allocated to nonrice crops. Land is mostly left fallow during the dry season. Irrigation permits rice production in both the wet and dry seasons in the irrigated area. As a result, cropping intensity in the irrigated area is higher than in the rainfed area. However, only 60% of the area is planted to rice during the dry season. The supply of irrigation water is probably not sufficient to grow a dry-season rice crop in all of the irrigated area. In addition, farmers may choose not to grow rice on all their land for a variety of reasons.

According to farmers' classification of land types, fields located at higher elevations account for almost 68% of the total rainfed area. The corresponding value for irrigated areas is only 28%. Thus, in terms of topography, most of the fields in rainfed areas are located at higher elevation. Field location tends to be correlated with field hydrology, which is an important determinant of the choice of crop establishment method. The average farm size is slightly higher in rainfed areas (3.3 ha) than in irrigated areas (3.0 ha).

To estimate the adoption rate of direct seeding, farmers were asked when they first adopted direct-seeding methods. Figure 5 shows the adoption trend of direct seeding in rainfed areas during the wet season. Only a small proportion of sample farmers adopted direct seeding during 1970-89, increasing dramatically after 1989. By 1998, about 90% of the farmers in the rainfed area had adopted DSR in the wet season. However, very few farmers adopted WSR in rainfed areas. The lack of irrigation water, low labor requirement, and low production cost were the major reasons reported by farmers for adopting DSR. These farmer incentives to switch to dry seeding were

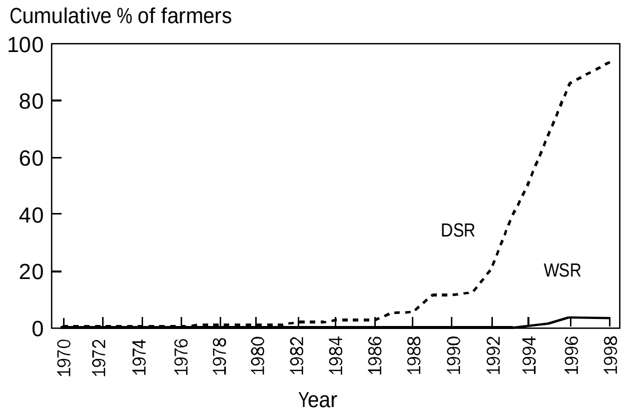

Fig. 5. Adoption of direct seeding in rainfed areas during the wet season in Khon Kaen, Thailand. DSR = dry-seeded rice, WSR = wet-seeded rice.

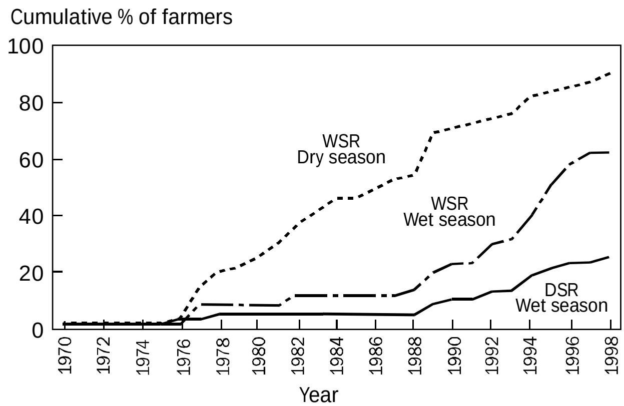

Fig. 6. Adoption of direct seeding in irrigated areas in Khon Kaen, Thailand. WSR = wet-seeded rice, DSR = dry-seeded rice.

reinforced by an active extension campaign to promote the method during the late 1980s and an increasing availability of tractors for land preparation under dry conditions.

The adoption of direct-seeding methods started much earlier in irrigated areas than in rainfed areas. The practice spread rapidly after 1976 for the dry-season crop and after 1988 for the wet-season crop (Fig. 6). The most popular direct-seeding method used during the wet season is WSR, which was adopted by 62% of the farmers by 1998. DSR is not as popular as WSR in irrigated areas. The lower production cost and lower labor requirement compared with TPR were the main reasons reported by farmers for adopting WSR.

Of the two direct-seeding methods, only WSR was adopted by farmers in irrigated areas during the dry season. Wet seeding during the dry season was adopted much earlier (in the late 1970s) than during the wet season, probably because of hydrological conditions in the field during the dry season. Water in the field is easier to manage in the dry season since it comes only from irrigation. Water management to provide optimal growing conditions for WSR is more difficult in the wet season than in the dry season. Overall, the increase in adoption rate of direct-seeding methods in both ecosystems coincided with the rapid increase in agricultural wage rate brought about by the fast economic growth in Thailand (Fig. 7).

In terms of area covered, the most popular method of establishment for the period 1996-97 to 1998-99 in the rainfed area during the wet season was DSR (Table 3). In the irrigated area, TPR was as popular as WSR during the wet season, but, during the dry season, rice was grown only by wet seeding. It is somewhat surprising to find that about 50% of the rice in the irrigated area is still being transplanted in Khon Kaen, where rapid commercialization of rice production has occurred. The increase in area transplanted in 1998-99 could be partly due to the recent economic crisis, which caused family members to return to the farm. This resulted in greater availability of family labor for transplanting. The higher rice price following the devaluation of the baht may have also encouraged farmers to shift back to transplanting to obtain higher yield and income. In addition, farmers believe that TPR guarantees good-quality grains, whereas DSR produces more unhealthy grains, possibly because of the high competition with weeds. The rainfall pattern during the 1998 wet season may have also favored the expansion of area under transplanting since there was more rain than normal in April and May 1998-99 when the seedbed was prepared for wet-season rice.

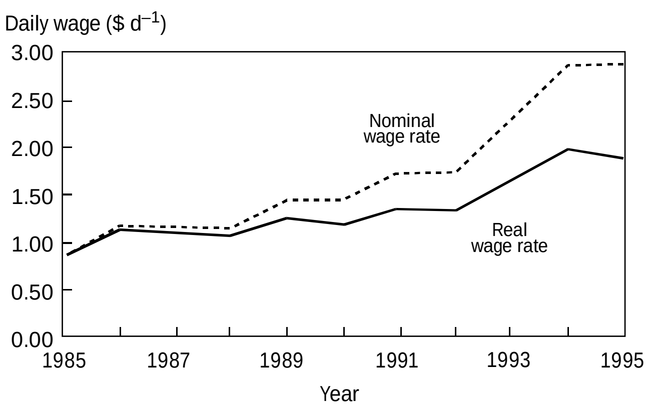

Fig. 7. Agricultural wage rates in Khon Kaen, Thailand. (Real wage rate obtained by using the consumer price index as the deflator.) Source: Bon (1998).

Table 3. Extent of direct seeding (% area) in Khon Kaen, Thailand, 1998-99.

Area[a]	Wet season			Dry season		
	1996-97	1997-98	1998-99	1996-97	1997-98	1998-99
Rainfed						
Total (ha)	322	320	322			
%						
TPR	17	17	27			
DSR	82	83	72			
WSR	0	0	1			
Irrigated						
Total (ha)	148	149	153	87	93	90
%						
TPR	44	45	52	0	1	0
DSR	8	8	9	0	0	0
WSR	47	47	39	100	99	100

[a]TPR = transplanted rice, DSR = dry-seeded rice, WSR = wet-seeded rice.

Table 4. Percentage area by field elevation and method of establishment in wet season, Khon Kaen, Thailand, 1998-99.

Area[a]	Rainfed			Irrigated		
	Low	High elevation	Both elevation	Low elevation	High elevation	Both
Total (ha)	114	208	322	129	24	153
%						
TPR	49	15	27	56	33	52
DSR	51	84	72	6	23	9
WSR	0	2	1	38	44	39

[a]TPR = transplanted rice, DSR = dry-seeded rice, WSR = wet-seeded rice.

The higher rainfall (273 mm) during that period compared with the average of 229 mm may have created field conditions more suitable for transplanting (Fig. 3).

The extent of adoption of direct-seeding methods in the wet season varies depending on field elevation. DSR is more common in high-lying fields than in low-lying fields in both rainfed and irrigated areas (Table 4). DSR is grown on 84% of high-elevation areas in the rainfed environment compared with only 51% in low-elevation areas. Likewise, DSR is used in 23% of high-lying fields in the irrigated environment compared with only 6% in low-lying fields. The low moisture-holding capacity of these high-lying fields may have encouraged farmers to dry-seed. In the irrigated environment, 56% of the area in low-lying fields is transplanted compared with only 38% for wet-seeded fields, perhaps because of water accumulation in low-lying fields. One-month-old seedlings of transplanted rice have a better chance of surviving than young seedlings of wet-seeded rice when fields become flooded during the early stage of rice growth.

Rice is established in more than 75% of the plots by the same method every year (Table 5). Switching of methods from year to year is minimal except in the rainfed area, where it was reported in 22% of the cases. According to farmers, the choice of establishment method was determined by the water status in the field during the initial stages of the wet season. Farmers said that they switched from DSR to TPR when water accumulation was excessive, and from TPR to DSR when water was limited. In irrigated areas, year-to-year variations in crop establishment methods occurred less frequently.

Table 6 shows the percentage of farmers who practice different methods of establishment. In the rainfed area, most farmers grow rice by dry seeding, with less than 16% practicing a combination of methods. In the irrigated area, about two-thirds grow rice by either transplanting or wet seeding. However, about one-third of the

Table 5. Percentage of plots with different methods of crop establishment during 1996-99.

Item	Rainfed area	Irrigated area	
	Wet season	Wet season	Dry season
Total plots (no.)	192	153	77
No switching			
TPR in 3 y (%)	18	45	0
DSR in 3 y (%)	60	10	0
WSR in 3 y (%)	0	33	97
Subtotal (%)	78	88	97
Switching			
TPR in 2 out of 3 y (%)	6	8	0
DSR in 2 out of 3 y (%)	16	1	0
WSR in 2 out of 3 y (%)	0	3	3
Subtotal (%)	22	12	3

Table 6. Percentage of farmers practicing different methods of crop establishment in Khon Kaen, Thailand, 1996-99.

Area	1996–97	1997–98	1998–99
Rainfed			
% of farmers using only one method	91	92	84
% of farmers using more than one method	9	8	16
Irrigated			
Wet season			
% of farmers using only one method	70	67	62
% of farmers using more than one method	30	33	38
Dry season			
% of farmers using only one method	100	100	100

farmers practice a combination of the two methods. Farmers gave several reasons for adopting more than one method of crop establishment. First, they use the most appropriate establishment method for plots with different elevations. For example, high-lying fields are mostly dry-seeded, whereas low-lying fields that have adequate moisture are mostly transplanted. Thus, farmers with plots at both low and high elevations reported using more than one method of rice establishment. Second, the use of more than one method helps to spread the demand for labor. When family labor is limited and rice has to be established within a short period, some parts of the farm are transplanted and some parts are direct-seeded. Third, using more than one method is also the farmers' way of distributing the overall risk. Prolonged drought after the onset of the rainy season makes dry seeding risky and late-season drought makes transplanting risky. The use of both methods tends to reduce the overall risk.

Rice yield and variability

Under experimental conditions, the yield performance of transplanting and direct-seeding methods is generally similar (Garcia et al 1995). However, survey results (Table 7) show that DSR yield is significantly lower than TPR yield in the rainfed environment. This is also true in irrigated areas. In rainfed areas where TPR is possible, some farmers reported shifting back to TPR because of low DSR yield. Farmers believe that high weed incidence is the major reason for low yield under DSR.

Variability as measured by the coefficient of variation of yield is higher in DSR than in other methods. Variability in cross-sectional data may be due to several factors, such as variations in input use, weed infestation, crop stand, farmers' skills, and crop establishment methods. We have not attempted to apportion total variability to these different sources because it is beyond the scope of this paper. However, dry seeding may have contributed to additional variability because of the difficulty in ensuring a uniform crop stand and high weed infestation.

Table 7. Average paddy yield by method of crop establishment in Khon Kaen, Thailand, 1998-99.

Item	Wet season					Dry season irrigated area
	Rainfed area		Irrigated area			
	TPR	DSR	TPR	DSR	WSR	WSR
Number of plots	65	128	89	17	59	87
Mean[a] (t ha^{-1})	2.5 a	1.0 b	3.2 a	2.8 b	3.2 a	3.5
Standard deviation	1.25	0.99	0.77	0.80	0.84	1.29
CV (%)	50	101	24	29	26	37

[a]Means with the same letter are not significantly different at the 5% level. The test on means was done for rainfed and irrigated areas separately.

Input use

A comparison of the input data shows that farmers use substantially more seeds in growing DSR and WSR than in growing TPR (Table 8). The use of a higher seeding rate may be the farmers' way of compensating for the low rate of seedling survival and establishment in direct-seeded fields under the dominant method of broadcasting. Labor use in direct-seeded fields is about 50% lower than in transplanted fields.

Weed infestation is an important factor that farmers consider in choosing an establishment method. Since weed infestation is generally more serious in DSR or WSR than in TPR, herbicide use is more common in direct-seeded plots than in TPR plots (Table 9). Manual weeding is not common in Khon Kaen, even among nonusers of herbicides. The only form of manual weeding practiced is removing weeds in spots with high weed infestation.

Land preparation is done mostly using 2-wheel tractors. The use of 4-wheel tractors is not common in Khon Kaen (Salokhe 1998). Farmers prefer to use 2-wheel tractors because 4-wheel tractors tend to damage bunds, making it difficult to retain water in the field. Animal draft power has been completely replaced by tractors for land preparation in Khon Kaen.

Costs and returns

The total production cost for TPR is higher than for other establishment methods regardless of water regime (Table 10). The difference is mainly due to the higher labor requirement for transplanting. The use of hired labor for TPR in rainfed areas is more than in irrigated areas. Apparently, farmers in rainfed areas hire more workers to complete transplanting within a short time before the field dries out. On the other hand, in irrigated areas where irrigation water is not limiting, the transplanting win-

Table 8. Input use by crop establishment method in Khon Kaen, Thailand, 1998-99.

Item	Wet season[a]				Dry season irrigated area (WSR)
	Rainfed area		Irrigated area		
	TPR	DSR	TPR	WSR	
Plot number	38	81	45	16	56
Material inputs					
Seeds (kg ha^{-1})	46 (20)	97 (126)	52 (31)	100 (33)	113 (43)
Fertilizer (kg ha^{-1})					
N	41 (26)	36 (20)	49 (28)	45 (28)	77 (44)
P	37 (36)	35 (21)	36 (20)	32 (23)	44 (34)
K	12 (11)	9 (12)	12 (12)	6 (8)	11 (14)
Power (d ha^{-1})					
Tractor	4.59 (2.50)	3.91 (2.46)	6.68 (4.25)	4.41 (1.76)	5.28 (2.65)
Harvester			0.01 (0.03)	0.03 (0.08)	0.30 (0.29)
Thresher	0.20 (0.20)	0.12 (0.13)	0.21 (0.12)	0.18 (0.15)	0.04 (0.11)
Labor (d ha^{-1})	86 (40)	36 (26)	74 (29)	40 (13)	31 (17)

[a]Values in parentheses are standard deviation.

Table 9. Weed control practices by crop establishment method in Khon Kaen, Thailand, 1998-99.

Item	Wet season[a]				Dry season irrigated area (WSR)
	Rainfed area		Irrigated area		
	TPR	DSR	TPR	WSR	
% frequency					
Nonusers of herbicide	76	67	51	12	14
Users of herbicide	24	33	49	88	86
Labor for manual weeding (person-d ha^{-1})					
Nonusers of herbicide	0.74 (1.98)	1.69 (4.38)	0.52 (1.33)	1.82 (0.00)	2.60 (5.63)
Users of herbicide	1.28 (1.94)	0.37 (1.25)	0.37 (0.56)	0.76 (1.28)	0.31 (0.89)
Cost of herbicide applied by users ($ ha^{-1})	3.65 (3.21)	14.50 (44.20)	5.26 (4.54)	5.61 (5.48)	7.92 (7.85)

[a]Values in parentheses are standard deviation. Exchange rate: $1 = 35 baht.

Table 10. Costs and returns ($ ha^{-1}) of rice production by crop establishment method in Khon Kaen, Thailand, 1998-99.

Item	Wet season[a]				Dry season irrigated area (WSR)
	Rainfed area		Irrigated area		
	TPR	DSR	TPR	WSR	
Gross income	395 (180)	171 (162)	570 (185)	548 (221)	512 (217)
Cash costs	275 (139)	146 (133)	183 (78)	164 (45)	203 (54)
Material inputs	72 (36)	59 (39)	69 (31)	63 (27)	94 (43)
Power	33 (26)	27 (24)	29 (21)	34 (29)	82 (22)
Labor	171 (137)	60 (104)	84 (67)	67 (57)	28 (25)
Noncash costs	188 (86)	141 (85)	221 (79)	144 (52)	131 (47)
Material inputs	4 (5)	10 (11)	6 (14)	5 (11)	3 (8)
Power	55 (57)	58 (68)	47 (22)	58 (35)	48 (26)
Labor	129 (96)	73 (62)	169 (87)	82 (46)	81 (49)
Total cash and noncash cost	463 (159)	287 (154)	404 (98)	308 (46)	334 (74)
Net return above cash cost	120 (210)	26 (140)	387 (185)	384 (246)	309 (220)
Net return above total cost	–68 (194)	–115 (153)	165 (179)	240 (226)	178 (222)
Ratio of net return to cash cost	0.43	0.18	2.11	2.34	1.52
Ratio of net return to total cost	–0.15	–0.40	0.41	0.78	0.53

[a]Values in parentheses are standard deviation. Exchange rate: $1 = 35 baht.

dow is much longer. Accordingly, farmers in irrigated areas use less hired labor but more available family labor by transplanting in a staggered fashion.

The net return above cash cost under rainfed conditions is very low for dry-seeded rice. Low yield is the major reason for low profitability. It seems somewhat paradoxical that the method that has become so popular in recent years should be yielding so low. Dry seeding is mostly practiced in upper fields where crops grow under drought conditions, whereas transplanting is used in fields with a more favorable water regime. Farmers actively choose fields with a more favorable hydrology for transplanting. Thus, the lower yield of a dry-seeded crop is not only due to the crop establishment method but also to the choice of less favorable fields for using this method. Overall, the profitability of dry-seeded rice is lower than that of transplanted rice. Farmers would not have been able to afford transplanting in these less favorable areas at a cost of \$275 ha^{-1}. With such a high cost, farmers would have been forced to stop growing rice in these less favorable fields where rice was traditionally established by transplanting. By saving labor, dry seeding probably helped produce rice from these less favorable upper fields and generate additional farm income.

As expected, returns are higher in irrigated areas than in rainfed areas. Net returns above cash costs in irrigated areas are similar for both transplanted and wet-seeded rice in the wet season. However, net returns above total cost are higher for wet-seeded rice because of savings in labor cost.

Net returns (when both cash and noncash costs are considered) are positive in irrigated areas but are negative in rainfed areas. Despite the negative net returns, farmers continue to grow rice in rainfed areas. The explanation probably lies in the way family labor is valued. When valued at the market wage rate, the imputed cost of family labor accounts for about 50% of total production cost. Farmers probably impute a lower valuation to family labor than what is reflected by the market wage rate.

Production function and technical efficiency

The quantity of nitrogen applied and field elevation were found to be statistically significant variables affecting rice productivity in both irrigated and rainfed areas (Table 11). The positive coefficient for lower fields indicates higher yields in these fields than in upper fields. In rainfed areas, transplanting has a clear yield advantage as indicated by the positive coefficient of the dummy variable for TPR. Early establishment in rainfed areas has a favorable effect on yield as indicated by the negative coefficient associated with the date of crop establishment. The favorable effect may be due to avoidance of terminal drought as a result of earlier crop establishment. In irrigated areas, later establishment seems to have a favorable effect as indicated by the positive coefficient associated with establishment date. This differential response to crop establishment date between irrigated and rainfed areas may reflect differences in varieties grown as well as favorable hydrological conditions in irrigated fields.

Estimated technical efficiencies by crop establishment method are shown in Table 12. Current technical efficiency levels show that farmers are slightly more efficient in growing rice by transplanting than by direct seeding. In rainfed areas, the average

Table 11. Factors affecting yield and technical efficiency during the wet season in Khon Kaen, Thailand, 1998-99.

Item[a]	Rainfed area[b]		Irrigated area	
Yield				
Intercept	7.61	(1.08) ***	6.44	(0.88) ***
Seeds (kg ha^{-1})	–0.02	(0.09)	0.03	(0.06)
Nitrogen (kg ha^{-1})	0.20	(0.10) **	0.13	(0.04) ***
Preharvest labor (person-d ha^{-1})	0.37	(0.08) ***	–0.01	(0.07)
Date of establishment	–0.54	(0.31) **	0.42	(0.22) **
Dummy for glutinous rice	–0.08	(0.23)	–0.23	(0.11) **
Dummy for low elevation	0.48	(0.13) ***	0.25	(0.09) ***
Sigma-squared	15.51	(12.91)	0.05	(0.01) ***
Gamma	0.99	(0.01) ***	1.00	(0.13) ***
Technical efficiency				
Intercept	–15.75	(16.76)	–0.24	(0.39)
Age (y)	–0.12	(0.09) *	0.00	(0.00)
Education (y)	1.75	(1.34) *	0.04	(0.02) **
Family size (no.)	–2.00	(1.62)	0.01	(0.03)
Farm size (ha)	0.89	(0.77)	0.03	(0.02) *
Dummy for farming as main occupation	4.16	(4.80)	–0.03	(0.15)
Log likelihood function	–141.00		20.62	
Log likelihood statistic for the one-sided error	59.69		10.41	
Sample size	119		61	

[a]Definitions:

Date of establishment	= 1 if 1st week of Jan.
	= 2 if 2nd week of Jan., etc.
Dummy for glutinous rice	= 1 if plot is grown to glutinous rice
	= 0 otherwise
Dummy for low elevation	= 1 if plot is at low elevation
	= 0 otherwise
Dummy for farming as main occupation	= 1 if farmer considers farming as the major source of income
	= 0 otherwise

[b]*, **, *** denote statistical significance at 10%, 5%, and 1% levels, respectively.

efficiency of 67% for transplanted rice implies that, for the same level of input, an average farmer establishing rice by transplanting produces 67% of the yield of the "best practice" farmer who transplants rice. In dry seeding, the corresponding figure is only 49%. However, for both methods, average yields are lower than those of "best practice" farmers by more than 1 t ha^{-1}. This yield gap indicates that better crop management practices that reduce the gap could have a potentially high payoff.

Do any farmer-specific factors determine technical efficiency? Table 11 presents the results of regression of technical efficiency estimates on a range of socioeconomic factors. Education is a significant factor that determines variability in technical efficiency in both rainfed and irrigated areas. More educated farmers have higher technical efficiency than less educated farmers. In addition, younger farmers in rainfed areas are more efficient than older farmers. In irrigated areas, farmers with larger farms

Table 12. Technical efficiency during the wet season in Khon Kaen, Thailand, 1998-99.

Item	Rainfed area		Irrigated area	
	TPR[a]	DSR	TPR	WSR
Plot no.	38	81	45	16
Technical efficiency				
Mean	0.67	0.49	0.73	0.73
Minimum	0.42	0.00	0.45	0.54
Maximum	0.88	0.91	0.96	1.00
Standard deviation	0.12	0.26	0.12	0.18
Observed yield (t ha^{-1})	2.6	1.1	3.2	3.0
"Best practice" yield (t ha^{-1})	3.9	2.3	4.5	4.2
Yield difference between "best practice" and observed yield (t ha^{-1})	1.3	1.2	1.2	1.1

[a]TPR = transplanted rice, DSR = dry-seeded rice, WSR = wet-seeded rice.

have a higher technical efficiency than those with smaller farms. These effects were found to be independent of the crop establishment method used.

Factors determining the adoption of direct seeding

Results of the probit analysis (Table 13) indicate that the major factors that determine the probability of adopting direct-seeding methods in rainfed areas are field elevation, labor-land ratio, farmers' perceptions of the extent of weed infestation, farmers' age, and major income source. Estimated marginal probabilities indicate that farmers are 29% less likely to adopt direct seeding in fields with lower elevation. Similarly, farmers who have an extra unit of labor relative to land operated are 61% less likely to adopt direct seeding. The better use of family labor can be achieved by transplanting when the operated land area is smaller relative to available labor. Fields that are more infested with weeds are less likely to be direct-seeded. The difficulty in controlling weeds in direct-seeded fields with a history of heavy weed infestation is obviously a deterrent to direct seeding. Farmers who do not consider farming as a major source of income are more likely to direct-seed because they may not have adequate time for labor-intensive transplanting. Older farmers seem less likely to direct-seed than younger ones probably because younger farmers are more interested in off-farm earning opportunities. Out of the five statistically significant variables for rainfed areas, two are biophysical factors and three are socioeconomic factors. In irrigated areas, none of the biophysical factors were statistically significant except for labor-land ratio and farmers' age. The effects of these significant variables are similar to those for rainfed areas.

Farmers' perceptions

Eight percent of the farmers in rainfed areas and 54% in irrigated areas reported never having tried dry seeding. Nonadopters believed that dry seeding increased weed

Table 13. Factors affecting adoption (probit analysis) of direct-seeding methods in Khon Kaen, Thailand, 1998-99.

Item[a]	Coefficient[b]	Standard error	Marginal probability
DSR in rainfed area			
Intercept	3.31	0.68	
Dummy for low elevation	–0.91 ***	0.21	–0.29
Labor-land ratio	–1.89 ***	0.58	–0.61
Weed perception dummy	–0.65 ***	0.22	–0.21
Age (y)	–0.02 **	0.01	–0.01
Major income source dummy	–0.63 ***	0.23	–0.20
Sample size	194		
Log likelihood ratio test statistic	55.45		
Chi-square value at 5% level and df = 5	11.07		
% of correct predictions	78		
WSR in irrigated area			
Intercept	1.06	0.79	0.37
Dummy for low elevation	–0.17	0.26	–0.06
Labor-land ratio	–1.36 ***	0.54	–0.48
Weed perception dummy	–0.28	0.24	–0.10
Age (y)	–0.01 *	0.01	–0.00
Major income source dummy	0.02	0.34	0.01
Sample size	165		
Log likelihood ratio test statistic	12.32		
Chi-square value at 5% level and df = 5	11.07		
% of correct predictions	65		

[a]DSR = dry-seeded rice, WSR = wet-seeded rice.
[b]*, **, *** denote statistical significance at 10%, 5%, and 1% levels, respectively.
Definition:

Dummy for low elevation	= 1 if plot is at low elevation = 0 otherwise
Dummy for weed perception	= 1 if farmer perceived the degree of weed infestation in the field as high = 0 otherwise
Major income source dummy	= 1 if farmer considers farming as the major source of income = 0 otherwise

infestation (56%) and reduced yield (33%). More than 90% of the farmers ranked transplanting as the highest-yielding method in the wet season. A majority of the farmers believed that DSR gave higher yield than WSR in rainfed areas and that WSR yielded higher than DSR in irrigated areas. This is consistent with the farmers' practice of growing TPR/DSR in rainfed areas and TPR/WSR in irrigated areas.

Farmers' choice of rice establishment method is normally based on biophysical factors such as weed incidence, water supply, field hydrology, and yield performance and socioeconomic factors such as labor requirement and cost and power for land preparation (Table 14). When good rainfall conditions permit, farmers in rainfed areas prefer to use TPR not only because of its high yield but also because of effective weed control, ease of land preparation, and favorable field hydrology. When condi-

Table 14. Farmers' responses (%) regarding factors considered in determining suitable crop establishment method during the wet season in Khon Kaen, Thailand, 1998-99.

Item	Rainfed area[a]		Irrigated area	
	TPR	DSR	TPR	WSR
No. of farmers responding	36	75	44	17
Reasons (% of farmers)				
Biophysical factors				
Weed incidence	61	35	75	71
Early/late start of rainy season	22	49	5	24
Field hydrology	17	8	27	6
Access to irrigation	17	12	27	29
High yields of TPR	17	9	23	0
Socioeconomic factors				
Labor availability and cost	17	47	27	53
Power for land preparation	22	13	20	24
Early harvest and price advantage	8	3	9	12
Guarantee of a second rice crop	0	1	0	0
To ensure rice harvest	3	1	2	0
Less risk	3	0	0	0
Others	6	0	4	6

[a]TPR = transplanted rice, DSR = dry-seeded rice, WSR = wet-seeded rice.

tions are unfavorable for transplanting, farmers use dry seeding to obtain some output while reducing production costs.

In irrigated areas, effective weed control, ease of land preparation, and access to irrigation were the major reasons why farmers preferred TPR and WSR to DSR. WSR was preferred over TPR because of low labor requirements, whereas TPR was preferred over WSR because of high yields. In fields with poor drainage, farmers preferred TPR to WSR because conditions were more suitable for TPR.

Conclusions

Labor saving and crop intensification are the two major reasons for the long-term shift from transplanting to direct seeding in Asia (Pandey and Velasco, this volume). In rainfed areas in Khon Kaen, northeast Thailand, the major driving force behind the shift has been the need to save labor since the wage rate escalated in the early 1990s. In irrigated areas, direct seeding may have facilitated double cropping of rice in addition to saving labor. However, the irrigated ecosystem represents only a small proportion of the total rice area in northeast Thailand.

Despite the switch to direct seeding, transplanting remains an important method of crop establishment in northeast Thailand, covering about 75% of the total rice area. The analysis revealed a range of biophysical factors (such as rainfall pattern, field elevation, field hydrology, degree of weed infestation) and socioeconomic factors (such as availability of family labor and wage rate) to be the major determinants of the adoption of direct seeding. Although the direct-seeding method (especially dry seeding) spread rapidly in northeast Thailand during 1989-93, the area covered by this method has now stabilized at around 25% of the rice area. This indicates that the spread of direct seeding may have approached an economically viable ceiling with the current technology. Further expansion of the method will require more effective methods of managing weeds and maintaining uniform plant density. These may involve better tillage, better land leveling, more appropriate seed placement, and improved nutrient management practices. Similarly, varieties with higher seed and seedling vigor and that can tolerate drought during early growth periods can improve the economics of dry seeding.

The pattern of the shift from transplanting to dry seeding in Khon Kaen indicates that farmers substituted dry-seeding methods mainly in upper fields while maintaining the area transplanted in lower fields with a hydrology more suitable for transplanted rice. Economic pressure from rapidly rising wage rates thus seems to have led to the substitution of direct seeding first in areas where environmental conditions are less favorable for higher yield. Farmer incentives for switching to dry seeding were also reinforced by an active extension campaign in the late 1980s to promote dry seeding and the increasing availability of tractors for dry land preparation. Growing rice in fields with poorer soil conditions using the traditional transplanting method would not have been economically viable because of the increased labor cost. Even with lower yields, dry seeding results in additional food and income at a substantially lower cash cost. Thus, a technology that resulted in less yield spread rapidly because of its economic advantage. Improvement of yield performance will certainly increase the area covered.

Although further improvements in direct-seeding technology are needed to improve yield and increase profitability, a substantial proportion of the area in northeast Thailand is likely to remain suitable for transplanting because of low elevation and poor drainage. In addition, dry seeding may not be feasible in some years because of excessive water accumulation in fields that are normally well drained. Thus, it is also desirable to continue investing resources to improve the productivity of transplanted rice and reduce its cost. One form of intervention that can reduce the cost of transplanted rice is the use of mechanical transplanters. Mechanical transplanters have been successful mainly in irrigated areas of East Asia and parts of China. Some design modifications may be needed to make such machines suitable in the more challenging environments of tropical Asia. Nevertheless, the rising cost of farm labor will continue to exert economic pressure that will drive the development of more cost-effective transplanting methods suitable to poorly drained areas.

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Notes

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Status of dry-seeding technologies for rice in Korea

M.-H. Lee, J.K. Kim, S.S. Kim, and S.T. Park

In 1991, direct-seeding technology in Korea was adopted and disseminated gradually to farmers. Farmers now practice two methods of direct seeding, dry and wet seeding. Dry seeding (seeding under dry conditions) has several advantages over wet seeding (seeding under flooded conditions), such as good seedling stand, lodging resistance, and less incidence of bird and fungi damage. In addition, less labor is required for tillage, seeding, and field management. Dry seeding is a method that uses a drill seeder attached to a tractor to plant 40 kg of dry seed ha^{-1} right after final land preparation. There are two different types of dry seeding—flat drill seeding for well-drained soils and high-ridged drill seeding for poorly drained soils.

Six direct-seeding varieties that are highly lodging-resistant and have good germination under low-temperature conditions had been developed and released to farmers by 1998. The ideal seeding time in Korea is from 20 April to 10 May when the daily mean air temperature is higher than 13 °C. Optimum seedling stand is 90–150 seedlings m^{-2}. The level of optimum nitrogen fertilizer is 150–180 kg ha^{-1}, which is 40–70 kg ha^{-1} higher than that for transplanting and wet seeding. However, phosphate and potassium are applied at the same rate of about 70 and 80 kg ha^{-1} as for transplanted and wet-seeded rice, respectively. An important technology for the success of dry seeding is effective weed control because the weed emergence period is longer than that of transplanting or wet seeding. Three systematic herbicide application methods are recommended during the dry period: either before or after rice seedling emergence and during flooding. Once the seedling stand is established, the rice crop needs to be irrigated at the third-leaf stage, 25–30 d after seeding, requiring two or three mid-summer drainages to increase lodging resistance.

During the full cropping season, the labor requirement for dry seeding is 30% lower than that for machine-transplanted rice using semiadult seedlings. Overall, rice production costs using direct seeding are about 20% lower than those of machine-transplanted rice.

Rice is the most important crop in Korean agriculture in terms of value of output and area. It is the staple food in the Korean diet with a cultural significance beyond its economic status. It is the centerpiece of the Korean agricultural policy framework, which emphasizes food security.

Rice cultivation in the country shifted rapidly from machine transplanting to direct seeding to reduce production costs after 1990. During the early 1980s, the main target of rice cultivation in Korea was to attain the maximum yield for self-sufficiency in rice. Therefore, milled rice yield increased from 3.8 t ha^{-1} in 1975 to 5.2 t ha^{-1} in 1997. Since 1990, much emphasis has been on labor-saving technologies.

The socioeconomic situation has changed rapidly in the last 30 years, influencing the structure of agriculture. Industrialization led to the outflow of labor from rural areas to cities; therefore, labor quality and quantity declined sharply while labor cost increased day by day. The farming population of 37.5% in 1975 dropped to 9.7% in 1997 and is expected to decrease continuously (MOAF 1998). On the other hand, Korea's agricultural market was forced to open up internationally. The price of rice in Korea is higher than that of the world market because of its high production cost and high farm labor and land cost. To increase the competitive power of rice in the world market, the target of rice research should shift from maximum yield potential to labor-saving technology as in direct seeding and large-scale farming.

From 1991 onward, various new rice cultivation practices, such as machine transplanting of infant seedlings (8–10-d-old seedlings) and direct seeding, were developed to save on labor. Direct-seeding practices were established and disseminated to farmers. The cultivation area devoted to direct seeding showed an increasing trend. Since 1995, the area for direct seeding has covered 10% of the total paddy field. Of the direct-seeding area, the dry-seeding area was about 6% in 1998, slightly larger than the area for wet seeding. The government plans to increase the direct-seeding area up to 50% to reduce by 35% the cost of rice production by 2004.

This paper summarizes the status and practical technologies of dry seeding in Korea, particularly seeding methods, water management, weed control, and labor requirements. It also discusses future research plans for more stabilized rice cultivation in Korea.

Changes in rice cultivation

For the past 30 years, rice cultivation in Korea has changed remarkably because of the economic situation. Before 1970, the main target of rice cultivation was to maximize yield for food self-sufficiency. However, this has changed to labor-saving techniques and mechanization for lower production costs. Also, rice-growing area increased from 1.18 million hectares in 1970 to 1.24 million ha in 1990, but it decreased to 1.05 million ha in 1997. To increase rice production, the new high-yielding rice variety "Tongil" was developed and released to farmers in 1972, starting the Green Revolution in Korea. Grain yield has increased from less than 4.0 t ha^{-1} before 1975 to 4.5 t ha^{-1} in 1990 and 5.2 t ha^{-1} in 1997 in milled rice. However, total rice production in Korea has also changed from 3.9 million t in 1970 to 5.4 million t in 1997 (Table 1). This is one of the success stories in Korean agriculture.

Up to the late 1970s, most rice farmers intensively practiced manual transplanting for high yield. But rapid economic development led to the outflow of labor from rural to urban areas in industry and services, thus affecting the agricultural structure. Farmers needed labor-saving rice production technologies. Thus, mechanical rice transplanting technology was introduced. Starting in 1978, rice transplanting technology, also called semiadult seedlings with a 35-d nursery period, was developed and introduced to farmers. After 1979, machine-transplanted area increased and reached 95% of the total rice-growing area in 1993. Another machine-transplanting method, referred to as infant seedlings (8–10-d-old seedlings), was developed (Table 2).

Table 1. Changes in rice cultivation area and productivity in Korea.

Year	Area (000 ha)	Milled rice yield (t ha^{-1})	Total production (000 t)
1970	1,184	3.3	3,907
1975	1,199	3.9	4,627
1980[a]	1,120	3.0	3,530
1985	1,233	4.6	5,618
1990	1,242	4.5	5,600
1992	1,156	4.6	5,328
1994	1,102	4.6	5,058
1996	1,049	5.1	5,322
1997	1,052	5.2	5,448

[a]Damaged by low temperature.

Table 2. Changes in rice cultivation area by three rice-planting methods in Korea (unit: 1,000 ha).

Year	Hand transplanting	Machine transplanting	Direct seeding
1978	1,217	2	–
1980	1,154	66	–
1982	1,042	171	–
1984	996	229	–
1986	868	365	–
1988	579	678	–
1990	201	1,044	3
1992	83	1,070	8
1994	30	999	73
1995	20	919	118
1996	17	920	110
1997	13	929	111

Source: Agricultural Statistics (1998): Ministry of Agriculture and Forestry, Seoul, Korea.

Table 3. Changes in direct-seeding area in Korea (RDA 1998).

Method	Area (000 ha)						
	1991	1992	1993	1994	1995	1996	1997
Dry seeding	0.3	1.7	3.6	35.3	67.7	65.2	57.2
Wet seeding	0.6	1.0	4.0	37.5	49.8	45.2	53.4
Total	0.9	2.7	7.6	72.8	117.5	110.4	110.6

At the end of the 1980s, Korean agriculture went through another adjustment as a result of the Uruguay round of the General Agreement on Tariffs and Trade and World Trade Organization policies, such as an open international agricultural market. To overcome this difficulty, new rice cultivation methods were developed. Starting in 1991, various direct-seeding methods to increase labor productivity were developed and introduced to farmers. The cultivation area devoted to direct seeding showed a remarkably increasing trend from 1993 onward. In 1995, the area devoted to direct-seeded cultivation increased to 117,500 ha, which is 11% of Korea's total rice area. The area devoted to direct seeding is expected to increase further through future improvements of cultivation techniques (Table 3).

Improved rice varieties for direct seeding

The goal of rice breeding is determined by changes in the socioeconomic situation, consumers' preferences, cultivation technologies, and the environment. The ideal plant type requirement for direct seeding was described by Dingkuhn et al (1991) as follows: has increased productivity, low tillering, and high sink capacity. Moreover, plant traits should include high seedling vigor, sustained high N concentration, reduced leaf growth during the late vegetative and reproductive growth stages, long life span, large flag leaf, and prolonged ripening phase. In addition, Ando (1995) cited lodging resistance and low-temperature germination ability as the most important characters for direct seeding. For direct seeding to succeed, suitable varieties have to be developed. The major criteria for selecting varieties for direct-seeded rice in Korea are good germination character under low-temperature conditions, higher seedling stand, lodging resistance, rooting habit, and early maturity as well as good grain quality with high yield (Park et al 1995, Yun 1999).

Six direct-seeding varieties, including three for medium maturity (Nonganbyeo, Juanbyeo, and Ansanbyeo) and another three for mid-late maturity (Donganbyeo, Daesanbyeo, and Hwamyeongbyeo), were recently developed and released to farmers (Table 4). These varieties have short plant height, lodging resistance, and good germination ability under low temperature. In addition, based on research results, 50 cultivars (17 early, 16 medium, and 17 mid-late maturity) were selected for direct seeding throughout the country. Many promising breeding lines are continuously developed under both dry and wet conditions at research stations. These semidwarf varieties

Table 4. Varieties developed for direct seeding in Korea (RDA 1998).

Maturity	Variety	Year released	Plant height (cm)	Lodging resistance	Milled rice yield (t ha^{-1})[a]
Medium	Nonganbyeo	1993	76	Strong	5.2
	Juanbyeo	1994	71	Strong	5.0
	Ansanbyeo	1995	70	Strong	5.1
Mid-late	Donganbyeo	1996	78	Strong	5.3
	Daesanbyeo	1996	80	Strong	5.4
	Hwanyeongbyeo	1997	80	Strong	5.1

[a]Milled rice recovery = 72%.

generally showed high lodging resistance and good grain quality. The milled rice yield of direct-seeding varieties is more than 5.0 t ha^{-1}.

Optimum seeding time

The rice-growing period in Korea is strictly from May to October. Air temperature is the main constraint to rice cultivation. However, soil conditions, regional microclimate, and, directly or indirectly, maturity influence the optimum seeding time for direct-seeding cultivation. Seeding begins when the daily mean temperature is higher than 13–15 °C. Seeding at 13 °C and 15 °C in the dry paddy field takes 17 and 15 d for seedling emergence, respectively, which is approximately in late April in the Suwon area (Lim et al 1991). Days to seedling emergence and number of seedling stand are influenced by soil temperature and moisture content. Research results indicated a negative relationship between soil temperature and days to emergence (Park et al 1991). Seedling stand was better at 60–80% soil moisture content until 8 d after seeding at 20 °C soil temperature. However, under low soil temperature conditions, a high seedling stand was obtained at 40–60% soil moisture content (RDA 1992).

Optimum seeding time in Korea depends on the region and maturity of the variety (Kim et al 1991, Kim SK et al 1992). April 20 is a critical early limit of seeding time, whereas 15 May in the northern region, 20 May in the middle region, and 25 May in the southern region are the critical late limits for early maturing varieties. On the other hand, the critical late limit for seeding of medium-maturing varieties is 5 d earlier than that of the early maturing varieties, whereas, for mid-late maturing varieties, the limit is 10 d earlier (Table 5).

Seeding rate

Since seeding rate is closely related to seedling stand, growth, and grain yield of rice, the crop should be seeded at the optimum rate. The seeding rate should also be determined when considering germination ability, seeding time, and seed size. Dela

Table 5. Optimum seeding time in direct-seeded rice on dry paddy (RDA 1997).

Region	Maturity		
	Early	Medium	Mid-late
Middle and northern	20 April-15 May	20 April-10 May	20 April-5 May
Middle	20 April-20 May	20 April-15 May	20 April-10 May
Southern	20 April-25 May	20 April-20 May	20 April-15 May

Table 6. Nitrogen application method under different seedling stands (Kang 1997).

Seedling stand (no. m^{-2})	Amount of N (kg ha^{-1})	N split application (kg ha^{-1})					Milled rice yield (t ha^{-1})
		Basal	3LS[a]	5LS	7LS	PI	
<90	190	–	80	65	–	45	6.0
90–150	150	–	60	45	–	45	5.8
>150	110	–	10	10	45	45	5.7

[a]LS = leaf stage, PI = panicle initiation stage.

Cruz and Padolina (1998) reported that the average seeding rate in farmers' fields varies greatly, from 100 to 230 kg ha^{-1}, depending on the growing season and region in the Philippines. In addition, most of the farmers that practice direct seeding in Korea are increasing the seeding rate by more than 60 kg ha^{-1}.

In general, the optimum number of the seedling stand in dry seeding is approximately 90–150 seedlings m^{-2}. The marginal number of seedlings m^{-2} is lower than 60 and higher than 200 (Lee et al 1989). In connection with this, the Rural Development Administration (RDA) recommended the optimum seeding rate per hectare as 50–60 kg in flat drill seeding and 40–50 kg in high-ridged drill seeding.

If the number of the seedling stand is lower than 90 seedlings m^{-2}, grain yield declines and rice quality is poor because of low panicle number m^{-2} (Table 6). On the other hand, the stand was prone to lodging and susceptible to diseases when it was higher than 200 seedlings m^{-2}. In this case, Kang (1997) observed that the number of panicles can be controlled by a topdressing of nitrogen.

Seeding method

Land preparation and seeding for dry-seeding rice cultivation are done by tractor under dry soil conditions. The initial plowing is done just after harvest in October and the second plowing is done in early spring. A two-time rotavation with the tractor should be done 1 or 2 d before seeding and the final rotavation should be done coinciding with seeding. Land leveling is one of the most important cultural practices to improve seedling stand and water, nutrient, and weed management in dry seeding (Yun 1999). A laser-leveling system was introduced to make land uniform before seeding (Table 7). There are two different types of dry seeding: flat drill seeding for well-drained soil and high-ridged drill seeding for ill-drained soil.

Table 7. Effect of laser-level scraper on land level (NCES 1997).

Treatment	Difference of land level (cm)		Seedlings (no. m^{-2})
	Before	After	
Laser scraper	9.5	3.6	118
Control	9.5	8.0	87

Table 8. Effect of drainage on silty and sandy loam soil just after seeding (NYAES 1995).

Soil structure	Treatment	Seedling emergence (d)	Seedling stand (no. m^{-2})	Milled rice yield (t ha^{-1})
Silty loam	Control	17	84	4.5
	Canals with 5-m interval	15	105	4.7
Sandy loam	Control	16	88	4.3
	Canals with 5-m interval	15	116	4.8

With flat drill seeding, seeds are sown in 2–3-cm soil depth by 6-, 8-, and 10-row drill seeders that are attached to a tractor during final land preparation. Flat drill seeding is more efficient than high-ridged drill seeding in seeding and harvesting. However, there are many risks in establishing seedlings in ill-drained soil or unleveled paddy fields, particularly when rain comes during and after seeding. Water management is not easy in the flat drill seeding method. Prolonged drought or submerged conditions after seeding often delay germination and reduce seedling stand. Flat drill seeding needs a small canal at 5-m intervals for irrigation and drainage to control moisture conditions on the soil surface after seeding. In a drainage plot using a small canal when heavy rains came just after seeding, seedling emergence was 1–2 d earlier than in the control and milled rice yield increased 5–12% because the number of the seedling stand increased (Table 8).

To reduce the damage from drought and submergence after seeding, the high-ridged seeding method was developed. This method uses small drainage canals (25-cm width and 12-cm depth) at 1.5-m intervals. The canals are automatically laid out by a rotovator.

There are two types of seeding: drill seeding by a 6-row seeder and broadcasting. Kim SC et al (1992) summarized the advantages and disadvantages of these two types of seeding as follows (Table 9). When seed was placed deeper than 5 cm, the number of days to seedling emergence increased and seedling stand decreased remarkably. Seedling growth was also very poor in relation to the optimum seeding depth (Table 10). When shallow seeding occurs, however, seeds are sometimes damaged by birds just after seeding and the plants suffer lodging after the heading of rice.

Table 9. Advantages and disadvantages of different dry-seeding methods (Lee 1995).

Seeding method	Advantages	Disadvantages
Ridged drill seeding	Uniform seedling stand and initial growth Possibility of emergence time prediction by irrigation during drought Promotes early herbicide effect	Effect of climate and soil condition Low efficiency of seeding work Slight difficulty for combine-harvesting
Flat drill seeding	Enhances seeding efficiency soil condition Slow emergence prediction	Effect on climate and

Table 10. Effect of seeding depth on seedling stand and seedling growth of rice in dry seeding (NCES 1991).

Seeding depth (cm)	Seeding rate (%)	Days to emergence	Seedling growth (35 DAS)[a]		
			Plant height (cm)	Dry weight (mg plant^{-1})	
				Shoot	Root
1	78	18	12.7	32.9	18.1
3	65	20	11.8	39.0	21.6
5	65	29	10.2	23.8	15.2
7	38	35	8.6	13.6	9.3

[a]DAS = days after seeding.

Fertilizer application

In dry-seeding rice cultivation, the right timing of nitrogen fertilizer application is critical because the rice plant needs 25–30 d longer in the field than with transplanted rice. Moreover, preparation under dry conditions leads to water and nutrient loss because of leaching and seepage. Early studies (Park et al 1990, Yun et al 1993) indicated that, in dry-seeding rice cultivation practices, N fertilizer must be applied 40–50% more than in transplanted rice in Korea. Kim et al (1995) reported that the optimum amount of N application is different depending on soil texture. Sandy loam soil requires 180–210 kg ha^{-1}, whereas loam soil requires 150–180 kg ha^{-1} (Table 11). However, the RDA recommends the optimum amount of N based on heading date, field lodging, and grain yield. Around 150–180 kg ha^{-1} in an ordinary field and 170–200 kg ha^{-1} in sandy loam soil must be applied. Incidentally, the high amounts of N application usually lead to disease susceptibility and field lodging. Phosphate and potassium are applied at 70 kg ha^{-1} and 80 kg ha^{-1}, respectively, in transplanted rice.

Tillering capacity and panicle number are not limiting factors in direct-seeded rice (Peng et al 1998). Therefore, N fertilizer should be applied as a topdressing to promote panicle size and grain filling. Optimum N split application methods are recommended

Table 11. Effect of different nitrogen levels on soil texture (Kim et al 1995).

Soil texture	Nitrogen level (kg ha^{-1})	Seedling stand (no. m^{-2})	Heading date	Field lodging (0–9)[a]	Milled rice yield (t ha^{-1})	Index
Sandy loam	150	163	18 Aug.	0	4.7	100
	180	172	18 Aug.	1	5.0	107
	210	157	19 Aug.	3	5.5	119
Loam	150	165	18 Aug.	0	4.8	100
	180	172	18 Aug.	3	5.5	115
	210	163	19 Aug.	5	5.9	122

[a]On a 0–9 scale, where 0 = no lodging and 9 = 100% lodging.

Table 12. Optimum nitrogen split application method for rice dry seeding (NCES 1994).

Nitrogen split application rate (%)					Field lodging[b]	Milled rice yield (t ha^{-1})	Index
Basal	3rd-leaf	5th-leaf	7th-leaf	PI[a]			
40	0	30	0	30	1	5.1	100
0	40	0	30	30	3	5.4	107
10	30	0	30	30	3	5.5	109

[a]PI = panicle initiation. [b]On a scale of 0–9, where 0 = no lodging and 9 = 100% lodging.

for higher yields in dry-seeded rice. Split application can be done in two ways: three times at the 3rd-leaf, 7th-leaf, and panicle initiation stage with 40%, 30%, and 30% or four times at the basal, 3rd-leaf, 7th-leaf, and panicle initiation stage with 10%, 30%, 30%, and 30%, respectively. These two N split application methods increased grain yield by 7–9% compared with the conventional split application method (Table 12).

Water management

Water management differs widely between direct seeding and transplanting, and between dry seeding and wet seeding. An advantage of direct seeding over transplanting is its lower water requirement (Kim SK et al 1992, Pandey and Velasco, this volume) and higher water-use efficiency (Gajendra 1994). Lee (1995) cited a series of experiments on water requirement in direct seeding. In dry seeding, seeding is done under dry conditions and continues for 25–30 d after seeding. The total irrigation water requirement in dry seeding is 110 mm higher than in transplanting because the percolation loss is 300 mm more. However, less water is required for land preparation (Table 13).

If the soil is too dry after seeding, irrigation through canals to maintain soil moisture content can significantly improve seedling stand (NYAES 1995). Permanent irrigation starts at the 3rd–4th-leaf stage of rice. Irrigation before this stage will increase the water requirement because the flooding period is longer; however, weed control is

Table 13. Total water requirement for dry-seeding and transplanting rice cultivation (Lee 1995).

Item	Transplanting (mm)	Dry seeding (mm)
Evaporation	300	300
Transpiration	550	480
Percolation	500	800
Land preparation	120	0
Total	1,470	1,580

Table 14. Effects of different drainage periods on dry seeding (NHAES 1991).

Water management	Plant height (cm)	Field lodging[a]	Filled grain (%)	Green grain (%)
Continuous flooding	87	9	92	8.3
Drain 20 DAF	84	5	92	5.4
Drain 20 and 30 DAF	84	1	93	2.8
Drain 20, 30, and 40 DAF	81	0	93	1.2

[a]DAF = days after flooding. [a]On a scale of 0–9, where 0 = no lodging and 9 = 100% lodging.

easier. To increase root activity and lodging resistance, two or three mid-summer drainages are needed at 10-d intervals beginning 20 d after permanent irrigation (Table 14).

Weed control

In addition to water management, weed control is important for the successful production of direct-seeded rice. In dry seeding, the amount of weeds and the weed community increased two- or threefold compared with wet seeding or transplanting. This is because weed seed germinates 6–10 d earlier than rice seed under low-temperature conditions (Park et al 1991). Yield loss without effective weed control can reach 70–100% in dry seeding versus only 10–35% for machine-transplanted rice (Park et al 1997). Therefore, weed control is a key factor in dry-seeding rice cultivation.

There are two distinct periods in dry seeding: the dry period (25–30 d after seeding) and permanent flood period. For successful weed control during the dry period, three alternative stages, 0–5, 12–15, and 25–30 d after seeding, are the optimum time for herbicide applications (Table 15). For the flood period, herbicide can be applied 3–5, 10–20, and 35–45 d after flooding (Table 16).

For effective weed control in dry seeding, the RDA (1997) recommends three systematic herbicide application methods depending on weed population and species. First, in rice fields with a low weed population, farmers can choose one application method among three (basic application systems): 0–5 d after seeding + 3–5 d after

Table 15. Recommended herbicides during the dry period (RDA 1997).

Application time	Herbicide
0–5 DAS[a] (preemergence)	Butachlor Thiobencarb Pendimethalin Bifenox/pendimethalin
12–15 DAS (rice emergence stage)	Propanil/butachlor Propanil/pendimethalin Propanil/molinate Propanil/thiocarb
25–30 DAS (foliar application)	Propanil 2,4-D Bentazon Cyhalofop/cinosulfuron/propanil Cyhalofop/bentazon Cyhalofop/pendimethalin Fenoxaprop/bentazon

[a]DAS = days after seeding.

Table 16. Recommended herbicides during permanent flood period (RDA 1997).

Application time	Herbicide
3–5 DAF[a]	Pyrazosulfuron-ethyl/butachlor Pyrazosulfuron-ethyl/thiobencarb Pyrazosulfuron-ethyl/mefenacet/dymron Butachlor Thiobencarb
10–20 DAF	Azimsulfuron/cyhalofop-butyl/molinate Imazosulfuron/mefenacet/dymron Cyhalofop-butyl/imazosulfuron/pretilachlor Bensulfuron-methyl/molinate
35–45 DAF	2,4-D, cyhalofop/cinosulfuron/propanil Cyhalofop/bentazon Cyhalofop/pendimethalin Fenoxaprop/bentazon Ethoxysulfuron/propanil Bentazon

[a]DAF = days after flooding.

flooding, 12–15 d after seeding + 3–5 d after flooding, and 25–30 d after seeding + 10–20 d after flooding. Second, when the field has many *Echinochloa* species, one of the following four application methods should be selected: 0–5 d after seeding + 12–20 d after seeding + 10–20 d after flooding, and three basic application systems + 35–45 d after flooding. Finally, for the field with many broadleaf weed species, one of the three basic application systems + bentazon at 35–45 d after flooding can be used (Table 17).

Table 17. Recommended herbicide application system in dry-seeded rice (RDA 1997).

Field condition		Dry period (DAS)[a]			Flooded period (DAF)[b]			
		0–5	12–15	20–25	3–5	10–20	35–45 a	35–45 b
Moderate paddy field	a	✓			✓			
	b		✓		✓			
	c			✓		✓		
Many weed species	a	✓		✓	✓	✓		
	b	✓			✓		✓	
	c		✓				✓	
	d			✓		✓	✓	
Many broadleaf weed species	a	✓			✓			✓
	b		✓		✓			✓
	c			✓		✓		✓

[a]DAS = days after seeding. [b]DAF = days after flooding.

Table 18. Occurrence of weedy rice in association with cultivation years of dry seeding (NYAES 1995).

Tillage	Occurrence of weedy rice (no. m^{-2})			
	1st year	2nd	3rd	4th
Autumn tillage	1	8	23	28
Spring tillage	0	6	15	32
No tillage	1	20	45	59
Control (wet seeding)	–	–	–	3

Weedy rice is another problem in dry seeding in Korea. It is widespread and rapidly increasing with the adoption of dry-seeding cultivation technology (Table 18). Infestation of rice fields by weedy rice results in economic losses because of reduced quality and lower yields. There are not many effective herbicides or methods to control weedy rice. Weedy rice has low-temperature germination ability. The seedling emerges 5–10 d earlier than rice (Chung 1998). Therefore, some farmers spray nonselective herbicides 8–10 d after seeding just before rice seed germination.

Economics of direct seeding

The yield potential of direct seeding is generally 5–10% lower than that of transplanting. However, several studies indicated that the yield potential of direct seeding was less than or equal to that of transplanted rice (Hong and Park 1992, Chung 1995, Park et al 1995, Tada and Morooka 1995, Park et al 1997). The RDA surveyed grain yield in farmers' fields using direct seeding and transplanting for 7 years from 1991 to 1997. Results showed that yields of dry-seeded rice were 4–7% lower than those of transplanted rice for the first 3 years. However, there were no differences in rice yield potential between machine transplanting and direct seeding thereafter (Table 19). Yield potential variation among farmers was greater for direct seeding than for transplanting. This is probably because of farmers' field management techniques, including seeding rate, weed control, water management, and other practices.

To analyze the economic effect of dry-seeded rice cultivation, the RDA (1997) summarized research results from 1994 to 1996. The labor requirement from tillage to seeding in dry seeding is 41 h ha^{-1}, which is 73% and 23% lower than that of machine transplanting and wet seeding, respectively. The total labor requirement for dry seeding is approximately 234 h ha^{-1}, which is 30% and 5% lower than that of semiadult seedling machine transplanting and wet seeding, respectively. However, the labor requirement is 8% higher for field management; water and weed control particularly require more labor than machine transplanting. Overall, the direct cost of rice production by direct seeding is about 21% lower than with machine transplanting (Table 20).

Table 19. Milled rice yield potential of direct seeding and machine transplanting in 1997, Korea (RDA 1998).

Year	Machine transplanting (t ha^{-1})	Dry seeding (t ha^{-1})
1991	4.7	4.4
1992	4.8	3.5
1993	4.5	4.3
1994	4.7	4.6
1995	4.7	4.6
1996	4.9	4.7
1997	5.1	5.1

Table 20. Labor requirement and rice production cost for machine transplanting and direct-seeded rice (RDA 1998).

Item	Machine transplanting		Direct seeding	
	Semiadult seedling	Infant seedling	Dry seeding	Wet seeding
Labor (h ha^{-1})[a]	154	115	41	53
Tillage-transplanting	164	158	177	182
Field management	334	291	233	245
Total				
Direct production cost (US$ ha^{-1})[b]	2,361	2,239	1,866	1,993

[a]Average of 3 y from 1994 to 1996. [b]Exchange rate: US$1 = 800 Korean won.

Research opportunities

Improved technologies for direct-seeding cultivation, including dry and wet seeding, would need a long time to become established. However, the following problems should be urgently solved to stabilize direct-seeding cultivation in Korea.

First, rice varietal improvement for direct-seeding cultivation is needed. Six new varieties for direct seeding have been developed and released to farmers and some varieties have been selected from recommended varieties for cultivation in the short term. In the long term, semidwarf rice varieties with a good seedling stand at low temperature, high seedling vigor, and lodging resistance should be developed for direct seeding. These varieties should be of the panicle weight type and have resistance to diseases.

Second, establishment of effective weed control systems and development of broad-spectrum herbicide are needed. In dry seeding, the labor requirement for weed control is higher than in transplanting or wet seeding. A control system for weedy rice should also be established as soon as possible because weedy rice is spreading very fast, particularly in dry-seeded paddy fields.

Third, new technology packages for stabilizing direct seeding are a prerequisite, such as optimum seedling stand, lodging resistance, weed control, fertilizer application methods, and water management, among others.

Fourth, as direct seeding is a mechanized system, a multipurpose seeding machine that combines drill seeding with fertilizer and herbicide application should be developed.

Finally, infrastructure improvement is required and improvements should focus on land rearrangement, such as proper size of area and grouping for optimal use of mechanization and irrigation systems.

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Seedling broadcasting in China: an overview

Tang Sheng-xiang

In recent years, China has developed an effective technique for rice plant establishment: seedling broadcasting. In 1995, the technique was applied to 98,700 ha. Because of its significant advantages of saving labor, reducing time between harvesting the previous crop and establishing a new rice crop, higher yield, and increasing farmers' total income, the area applied to this technique expanded rapidly to 6.7 million ha in 2000. This represents 21.8% of the total rice-growing area in China.

Four basic practical forms of seedling broadcasting are used: hand broadcasting seedlings produced by a wet bed, hand broadcasting seedlings produced by a dry bed, hand broadcasting seedlings produced by a dry bed with soft polyvinyl chloride (PVC) trays, and machine broadcasting seedlings produced by a dry bed with soft PVC trays. The third is the most popular method adopted by farmers in China. The area under seedling broadcasting increased fast in rice regions due to a higher labor cost, labor shortage, and short turnaround time in rice-rice and wheat-rice cropping systems, as well as in high-income rural areas. The key requirements for seedling broadcasting are good land preparation, good varieties, vigorous seedlings, suitable seedling density, and good water and weed management. This paper discusses the research areas for facilitating the development of this technique.

China is the world's largest rice-producing country with 31.2 million ha of rice, of which about 92.7% is irrigated to a different extent. Rice production was 190.4 million t, with a national average yield of 6.2 t ha^{-1} in 2000. The main rice-growing region in China is between 20° and 32°N, although recently northeast China, between 40° and 48°N, has become an important region for japonica rice.

Because of the rising labor cost and the shorter turnaround time in rice-rice and wheat-rice cropping systems, the so-called "light rice cultivation," such as direct seeding and seedling broadcasting for rice plant establishment, has been adopted in some rice regions in China. The technique of seedling broadcasting started in the 1980s, but developed slowly from 1989 to 1993 mainly because of the higher cost of materials used for producing seedlings such as hard plastic trays or hard paper rolls for seedling broadcasting. Seedling broadcasting has developed rapidly in recent years because of its significant advantages, as well as the use of low-cost soft polyvinyl chloride (PVC) trays for growing seedlings (MOA 1997, Cheng 2000).

This paper gives an overview of the development of seedling broadcasting in China; its advantages, requirements, and limitations; and research areas. All information reported here were compiled from published Chinese journals and reports.

Seedling broadcasting: the technique and its principal forms

There are three methods of rice establishment in China: transplanting, seedling broadcasting, and direct seeding. Seedling broadcasting involves broadcasting seedlings into puddled soil using either manual labor or machines. Seedlings (usually 2–4) with some soil in the root part are broadcast from about 2 m high on a puddled field so that the root part sinks 1–1.5 cm deep into puddled soil because of gravity. After 2–3 d, new roots grow and plants emerge.

Four basic forms of seedling broadcasting are practiced: hand broadcasting seedlings produced by a wet bed, hand broadcasting seedlings produced by a dry bed, hand broadcasting seedlings produced by a dry bed with soft PVC trays, and machine broadcasting seedlings produced by a dry bed with soft PVC trays. The third is the most popular technique adopted by farmers, occupying about 90% of the area devoted to seedling broadcasting in the country.

Several kinds of soft PVC trays with various numbers of holes are used for loading soil: 561 holes, 451 holes, 353 holes, etc. (Cheng et al 2000). For example, a PVC tray with 561 holes is 60 cm long and 33 cm wide, which is suitable for producing seedlings with 3–5 leaves. Each hole is about 1.8 cm high with a diameter of 1.9 cm on top and 1.1 cm at the bottom. Two to four grains are sown into each hole loaded with soil (Ye 1998). Soft PVC trays can be used repeatedly for three to four crops in a year.

Advantages

Seedling broadcasting has several advantages. First, it can significantly save labor for rice crop establishment. Usually, plant establishment by hand broadcasting seedlings needs 2–3 labor-d ha^{-1}, whereas hand transplanting in an irrigated field requires 15–30 labor-d ha^{-1} (Xie 1997). Machine broadcasting needs only 2–2.5 labor-d ha^{-1}, including seedling transportation from the seedling bed to the field and machine operation in the field (Su et al 1999). When all activities from sowing to crop establishment are accounted for (e.g., seedbed preparation, seeding, pulling, etc.), hand broadcasting seedlings can save a total of 54 labor-d ha^{-1} compared with hand transplanting, which needs a larger seedling bed and more labor for pulling out seedlings (Xu and Yu 1998).

Second, seedling broadcasting can reduce land use for the seedling bed. For 1 ha of rice crop establishment, seedling broadcasting needs 1,200–1,500 PVC trays (60 mm × 33 cm), which occupy about 500 m^2 of seedling bed (including the ditches). Transplanting requires 1,500–1,600 m^2 of seedling bed for the first crop of indica rice (Xu and Yu 1998, Liu 1998). Hybrid indica late rice needs only about 750 PVC trays for seeding 15 kg of seeds for 1 ha of rice (Liu and Li 1999). The area saved for seedling beds can be used to plant another crop to increase farmers' income; this especially benefits farmers with small landholdings.

Third, seedling broadcasting advances crop establishment. For most farmers with small lands, from harvesting the first rice or winter crop to completing transplanting of the second rice or single rice crop usually takes 10–15 d. With seedling broadcasting, this can be shortened to 6–10 d. The significant benefits come from obtaining higher yields in the second rice or single rice crop if plant establishment can advance 6–8 d because a low temperature in late autumn usually affects booting and flowering, resulting in low yield (MOA 1997).

Another advantage is higher yield. It was reported in Guangxi and Jiangsu provinces that yield could be 3–8% higher with seedling broadcasting than with transplanting (Table 1). The reasons for higher yield are earlier tilling (1–3 d earlier than transplanting), good root system development in the 1–10-cm soil layer, higher plant density, more panicles, and more filled grains (Xu 1999, Cheng et al 1999, Liao et al 1998). A national survey by the Ministry of Agriculture showed that, on average, seedling broadcasting yielded 573 kg ha^{-1} more than transplanting in a total area of 1.46 million ha during 1992-97 (Table 2). However, there was no significant difference in yield between crops established by seedling broadcasting and transplanting

Table 1. Comparison of yield components among hand broadcasting seedlings (HBS), hand transplanting (HTP), and machine broadcasting seedlings (MBS).

Year	Rice crop	Establishment method	Effective panicles (no. m^{-2})	Spikelets (10^3 m^{-2})	Filled grains (no. $panicle^{-1}$)	Filled grains (%)	1,000-grain weight (g)	Yield (t ha^{-1})
1996[a]	First	HBS	323.1	36.5	96.3	85.3	27.1	7.9
		HTP	281.7	33.6	102.1	85.6	27.3	7.3
	Second	HBS	317.4	36.9	103.8	89.3	29.0	8.2
		HTP	257.4	32.5	112.9	89.3	28.8	7.0
1997[b]	First	HBS	315.5	36.2	93.3	81.3	27.2	7.3
		HTP	276.5	33.1	97.6	81.5	27.1	6.8
	Second	HBS	304.8	34.7	90.6	79.7	25.7	6.7
		HTP	250.5	32.0	101.6	79.5	25.7	6.2
1997[c]	Single	MBS	423.0	44.3	91.5	87.4	28.7	9.8
		HTP	400.5	41.8	90.0	86.2	28.1	8.9

[a]Source: Xu (1999). The data are the average of 11 and 2 experimental sites in the first and second rice crops, respectively, in Guangxi Province. [b]Source: Xu (1999). The data are the average of 16 and 8 experimental sites in the first and second rice crops, respectively, in Guangxi Province. [c]Source: Liao et al (1998). Variety Wuyujin 3, japonica, 6.8 ha in Jiangsu Province.

Table 2. Yield difference between seedling broadcasting (SB) and transplanting (TPR) in 1992-97, China (MOA 1997).

Year	SB area (10^3 ha)	Yield difference (SB to TPR)	
		kg ha^{-1}	%
1992	6.5	+429.8	+6.1
1993	28.8	+499.5	+6.7
1994	61.1	+421.5	+5.3
1995	98.7	+531.0	+7.2
1996	277.3	+603.0	+9.0
1997	984.3	+581.1	+9.1
Total	1,456.7	+572.9	+8.6

Table 3. Economic benefits from hand broadcasting seedlings (HBS) of rice and hand transplanting (HTP) of rice, Jingzhou County, Hunan Province.

Method	Area (ha)	Yield (t ha^{-1})	Income (\$ ha^{-1})	Inputs (\$ ha^{-1})						
				Seed	Pesticide	Trays	Labor	Fertilizer	Others	Total
HBS	2.8	8.5	1,399	32	29	23	309	109	41	543
HTP	2.4	7.8	1,290	34	31	0	397	114	34	611
HBS to HTP	–	+0.7	+109	–2	–2	+23	–88	–5	+7	–68

Source: Liu (1998). The price of 100 kg of rough rice is \$16.50.

in some rice areas because of a lack of suitable varieties for seedling broadcasting (MOA 1997).

Another advantage of seedling broadcasting is that the economic benefits of applying seedling broadcasting come from higher yield and savings in labor and/or cost of field operations. The benefit varies from region to region. In Shanghai, farmers obtain \$135 more income ha^{-1} (\$73 from more yield and \$62 from less input) by seedling broadcasting than by transplanting (Min 1998). In Fujian Province, farmers save \$186 ha^{-1} with machine broadcasting than with hand transplanting (Su et al 1999). In Hunan Province (Liu 1998), farmers obtain \$177 more income ha^{-1} by hand broadcasting seedlings than by hand transplanting (Table 3). A survey in Zhejiang Province indicated an increase in income of 15.1–36.4% with hand broadcasting seedlings than with hand transplanting (Xu and Yu 1998). A national survey showed that on average farmers receive \$103 ha^{-1} more with seedling broadcasting than with transplanting (MOA 1997).

Development of seedling broadcasting in China

Since 1994, the area under seedling broadcasting has expanded rapidly, especially in areas with double rice-rice and wheat-rice cropping systems in central and southern China. The reasons why farmers adopted this technique are, first, the labor cost rose significantly in the 1990s, especially in those areas with fast economic development. Farmers adopted techniques that save on labor and require less difficult field work. Second, labor is scarce, especially in the spring and summer, because many young farmers go to factories and cities to work. Farmers could not finish all the field work such as harvesting the previous crop, land preparation, and crop establishment of the next rice crop by hand transplanting because of inadequate labor availability within the 10–15 d of high summer temperature. On the other hand, low temperature in late autumn (middle September to early October) unfavorably affects rice flowering and yield in double rice-rice and wheat-rice cropping areas. If establishment in the field is delayed for several days, rice may be exposed to low temperature at the late booting and flowering stages and paddy yield will decrease sharply. This situation requires an effective method that could complete rice plant establishment in fewer days with less labor and less field work. Another reason for farmer adoption is that the soft PVC trays, which are used for producing vigorous seedlings and for seedling broadcasting, proliferated since the early 1990s. These soft trays are much cheaper than hard plastic trays or hard paper rolls, and can be used repeatedly for 3–4 crops in a year. The trays greatly reduced the cost of seedling establishment and promoted the adoption of seedling broadcasting by farmers.

In 1991, the area covered by seedling broadcasting was only 1,200 ha in China. In 1992, a national key program for research and extension of seedling broadcasting was established. After several years, the area under seedling broadcasting increased rapidly to 0.7, 1.5, 2.9, 4.8, 6.0, and 6.7 million ha in 1995, 1996, 1997, 1998, 1999, and 2000, respectively. The method spread rapidly in the provinces of Guangdong (520,000 ha), Jiangsu (330,000 ha), Liaoning (160,000 ha), Jilin (130,000 ha), Hubei (70,000 ha), and Shanghai (60,000 ha) in 1996 (MOA 1997). In 1998, there were about 1.3 million ha under direct seeding and 4.8 million ha under seedling broadcasting, equivalent to 4.3% and 15.6% of the total rice area in China (Cheng 2000).

Basic requirements for the seedling broadcasting technology

Ideal rice variety

The most suitable plant type for seedling broadcasting is a modern variety with early tillering ability, fast root growth, a strong stem, and lodging resistance. For the double-rice cropping system in central China, varieties with short to intermediate duration of 110–125 d for first rice and 115–135 d for second rice are required for both indica and japonica types. Variety experiments showed that varieties with early and vigorous tillers and more effective panicles are suitable for seedling broadcasting to obtain high yields (Cheng et al 1999, Xu and Yu 1998, Zhong and Wu 1998). Most hybrid combinations and some conventional varieties with longer growth duration could be used for seedling broadcasting in the single rice and wheat-rice crop regions in central China (Jiang et al 1999).

Good land preparation

The rice field should be tilled and leveled well. When seedlings are broadcast, the field should be kept well puddled with no water layer or with only 0.5–1-cm water depth to avoid floating of seedlings. The field can be watered again after only 5–7 d of seedling broadcasting. Good water management is necessary for the technique to succeed.

Vigorous seedlings with suitable age

Vigorous seedlings are important. The suitable age of seedlings for broadcasting differs according to variety, planting season, soil texture, and method of producing seedlings. In general, varieties with short growth duration need young seedlings with 3–4.5 leaves. Seedlings produced by soft PVC trays should be younger (3–5 leaves) than those from traditional field beds (5–9 leaves). For machine broadcasting, the suitable seedling age is 20–25 d with 4–5 leaves and about 15–18 cm height for first rice and 15–25 d with 4–5 leaves and 18 cm height for second and single rice (Xie 1997). In some cases in Zhejiang Province, seedling age can be about 30–35 d for photoperiod-sensitive japonica varieties when hand broadcasting seedlings without trays.

Seedling density in the field

This differs according to variety used, seedling age, level of soil fertility, growth duration, and other parameters used. In South China, seedling density can be about 22.5 seedling-drops m^{-2} for first rice and 24–26 seedling-drops m^{-2} for second rice using PVC trays. A seedling-drop consists of 2–4 seedlings together. The density for a rice field with lower fertility is about 27 seedling-drops m^{-2} for first rice and 30 for second rice. In central China, 23–27 seedling-drops m^{-2} for hybrid rice and 30–38 for conventional varieties are suitable (Jiang et al 1999). Experiments in Fujian Province showed that the plant density of hybrid rice is about 60 seedlings m^{-2} (not seedling-drops) with hand broadcasting without the use of trays (Zheng et al 1998).

Weed control

As in direct seedling, weed problems in seedling broadcasting are more serious than in transplanting. To control weeds, herbicides can be applied with a water layer of 4–5 cm depth 5–7 d after broadcasting seedlings. The water layer should be kept for 3–5 d.

Limitations and research areas

Some problems constrain the adoption of seedling broadcasting by farmers or its extension by agricultural experiment stations in China.

1. Not all varieties are suitable for seedling broadcasting. In some regions, no suitable varieties for seedling broadcasting exist, especially in areas with a double rice-rice system that requires crops with short growth duration.
2. A good irrigation system is necessary. If water is not sufficient or does not come on time when the field is being prepared for seedling broadcasting, poor land preparation or an unleveled field will result, causing uneven rice plant

establishment, poor root initiation, and, finally, lower yield. Without good irrigation, it is difficult to apply the technique.

3. Poor weed management after seedling broadcasting causes lower or very low yield. In areas with serious weed problems, the cost of herbicides tends to be much higher in seedling broadcasting than in transplanting after plant establishment. Seedling broadcasting will not be adopted by farmers in areas with serious weed problems and lower income. Because of these limitations, it is estimated that seedling broadcasting could be applied to a maximum area of about 8 million ha, which is about 25% of the total rice-growing area in China, by 2005 (MOA 1997, Cheng 2000).

To facilitate the continuous development of the technique, these research areas should be given priority:

- Germplasm improvement for new varieties suitable for seedling broadcasting in different rice ecosystems, with emphasis on suitable growth duration, fast root initiation, a strong stem, resistance to diseases, and high yield.
- Technology for producing vigorous seedlings from a seedling bed without soft PVC trays.
- Technology for good water and weed management after seedling broadcasting.
- Machinery for seedling broadcasting.
- Economic and policy research to encourage farmers to apply seedling broadcasting.

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Notes

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Dry-seeded rice for enhancing productivity of rainfed drought-prone lands: lessons from Bangladesh and the Philippines

M.A. Mazid, S.I. Bhuiyan, M.A. Mannan, and L.J. Wade

In most rainfed drought-prone environments, water shortages constrain farm productivity toward the end of the season for the wet-season rice crop and/or for a second crop after rice. Dry seeding, instead of transplanting rice, may help solve this problem. Dry-seeded rice can be established and harvested earlier, with a reduced risk of drought to the crop and, at the same time, leave a longer favorable period for growing a postrice crop. Recent research has established the prospects of dry-seeded rice-based farming systems in drought-prone environments of various countries, including the Philippines and Bangladesh. This paper summarizes some of that research conducted within the auspices of the Rainfed Lowland Rice Research Consortium (RLRRC), a regional research network coordinated by IRRI. Some common issues that deserve further investigation are discussed.

Rainfed drought-prone rice lands in various parts of South and Southeast Asia have several common characteristics:

1. Rainfall is concentrated over a relatively short period, usually June-September in South Asia, leaving subsequent months very dry. The timing of the wet season is similar in Thailand and the Philippines, but not in Indonesia, where the wet season is usually from November to February.
2. The onset and cessation of the wet season can vary substantially from year to year, which may result in delayed wetland preparation. Consequently, transplanting of rice, which is the most common method of establishing the crop, may be delayed, requiring the use of older seedlings.
3. In the majority of years, the rice crop suffers a substantial yield reduction from drought stress during the critical reproductive or grain-filling stage because of the early cessation of rains.

4. Growing a postrice crop becomes difficult in most years and nearly impossible when the rainfall ceases relatively early, since the field is too dry for crop establishment after the rice harvest.

A remedy to these problems is to advance the establishment of the rice crop to minimize its exposure to late drought stress and to take advantage of a more hydrologically favorable postrice period to grow a profitable nonrice crop.

Recent research in the Philippines and in Bangladesh has shown that dry-seeding technology enables earlier crop establishment. In dry seeding, land is usually prepared dry or moist with the onset of preseason light showers and sowing of dry rice seeds. Seeds germinate in the moist soil with subsequent rain. This method contrasts with the popular transplanting method of rice crop establishment in the puddled field, which has been prepared under wetland culture. Direct seeding of rice has been a traditional, popular establishment method, especially in the summer (*aus*) season in Bangladesh. Because of the increasing pressure to intensify land use and productivity in the country, dry seeding offers considerable promise and economic advantages for farmers.

This paper synthesizes recent findings from research conducted in the Philippines and in Bangladesh, which assessed the potential of the dry-seeding technique of rice in drought-prone environments and its consequences for the success of postrice legume crops. Results allow consideration of the prospects for sustainable productivity enhancement in rice-based systems in rainfed drought-prone areas.

Dry-seeded rice in the Philippines

A study conducted by IRRI in collaboration with local farmers in Urbiztondo Municipality of Pangasinan during 1991-95 under the auspices of the Rainfed Lowland Rice Research Consortium (RLRRC) produced a significant body of information and literature on the technical and socioeconomic aspects of rice-based farming systems in the area, where dry seeding of rice has been gaining in popularity. The major findings from that research study, as they relate to the objectives of this paper, should provide useful comparisons with the situation in Bangladesh. The first section is essentially a review of that published work.

Materials and methods

Urbiztondo (15°48′N, 120°23′E), the research site, is located in Pangasinan Province in northern Luzon, Philippines. The dominant soil textures in the area are silty clay and silty clay loam. The site receives an average annual rainfall of about 1,500 mm, but the amount received during the 5-mo rice season (Jun-Oct) is highly variable. Additionally, as in the Rajshahi, Bangladesh, site, the onset and termination of the wet season vary from year to year and in-season droughts are frequent. The rice crop generally suffers from water stress. Studies conducted at the site during 1991-95 focused on scientific comparisons of transplanted vs dry-seeded rice systems of farmers in Urbiztondo in relation to drought risks, performance stability, weed management, cropping intensification, economic returns, and limitations to adoption.

Results and discussion

Cropping system changes. In the last decade, significant changes have taken place in Pangasinan Province, where rainfed rice grown in drought-prone environments constitutes the main livelihood of smallholders. In 1991-92, about 42% of the farms studied grew a single rice crop, keeping the land fallow both before and after the rice season (sample size: 30). At that time, 60% of the farmers transplanted the crop; the remainder used dry seeding. The preference for transplanting was related to ease of weed control with this method. On the other hand, those who preferred dry seeding cited advantages such as reduced labor cost for crop establishment and better prospects for a postrice crop, usually mungbean. As in most other rainfed areas of the Philippines, almost all farms in Urbiztondo grow modern rice varieties. The farmers' preference for a crop establishment method for rice changed significantly during subsequent years. The percentage of dry-seeded rice area in the municipality increased from about 20% in 1991 to 60% in 1995 (Fig. 1) (Lantican et al 1999).

Rainfall and crop establishment relationship. Early establishment of the wet-season rice crop enabled avoidance of drought stress. At the study site, the majority of farmers required a minimum of 600 mm of cumulative rainfall to complete puddling and transplanting operations, which occurred at various times of the year. When rains were late or low in intensity, transplanting was delayed and was often done using older seedlings. In some years, when rains were much delayed, farmers had to reestablish seedbeds or buy seedlings.

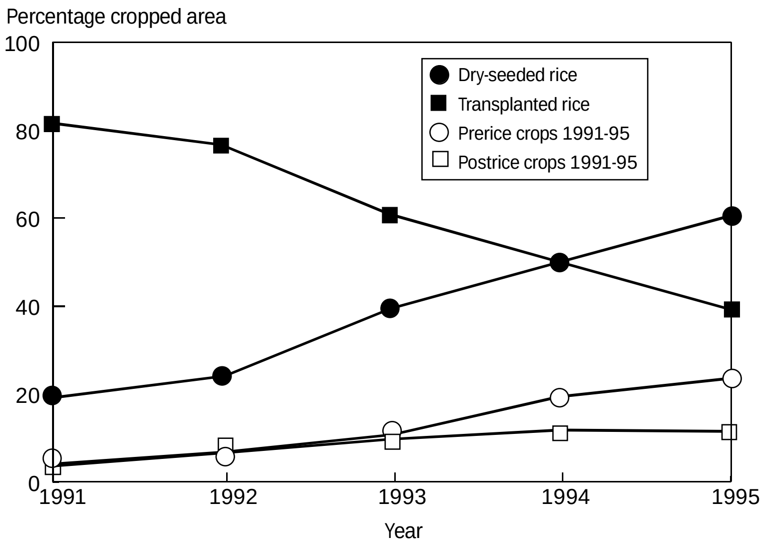

Fig. 1. Proportion of total rice area under dry-seeded rice and transplanted rice systems, and area of pre- and postrice crops during 1991-95 (total rice area = 3,026 ha) in Urbiztondo, Philippines.

In contrast, farmers completed dry seeding with only 150 mm of cumulative rainfall. With these minimal rainfall requirements, dry seeding in an average year (50% probability) would be completed by 1 June and transplanting by 21 July. In one year in four, rainfall would be insufficient for dry seeding until after 21 June and for transplanting until after 1 September (Saleh and Bhuiyan 1995). In 1991 and 1992, the established dry-seeded rice field in Urbiztondo received 402 and 425 mm of rainfall, respectively, before transplanted rice was established in the field.

Drought risk. The early establishment of dry-seeded rice allows a better use of rainfall by the crop and a better match between the vegetative and reproductive stages with more assured rainfall periods, which ultimately result in a higher water-use efficiency. Farmers using dry seeding were able to establish rice 47 d earlier in 1991 and 38 d earlier in 1992 than their counterparts who used transplanting to establish the crop. At 50% seasonal rainfall probability, both dry-seeded and transplanted rice would have adequate rainfall throughout the crop's life cycle. But, at 75% probability, transplanted rice would receive only about 50% of its water requirement from rainfall; in contrast, dry-seeded rice, which would be established about 40 d earlier, would receive enough rainfall to meet all its requirements (Saleh et al 1995).

Yield variability. Average yields of farms sown to dry-seeded and transplanted rice during the 1991-93 wet seasons were the same (2.9 t ha^{-1}) in Urbiztondo. When yield data were segregated into "high" (3.5 t ha^{-1} or more) and "low" (<3.5 t ha^{-1}), average yields from both crop establishment methods again did not differ significantly for these two categories. But, within the "high" group, variability in yields as estimated by the coefficient of variation was higher in dry-seeded rice fields. The greater variation in yields of dry-seeded rice was probably caused by fluctuations in the time and amount of early season rainfall, which affected crop establishment, and the effectiveness of weed control. For "low" yields, variability was about the same in both crop establishment groups (Lantican et al 1999).

Weed management. Dry-seeded rice faces more intense weed competition and may not produce any yield if weeds are left uncontrolled (Moody 1982, Fujisaka et al 1993). Farmers' weed control in dry-seeded rice was mostly inadequate, and the problem was exacerbated by the incorrect application of herbicides. Variability in weed infestation from year to year made weed control by herbicides a very complex operation for farmers.

Good weed management in dry-seeded rice requires skillful selection of herbicides for target weed species and their proper application (timing, concentration, and quantity). This requires knowledge and experience. Farmers aiming for high yields usually ensure that weeds are under control. Both high- and low-yielding dry-seeded rice farms in Urbiztondo spent nearly equal amounts of money on herbicides, but about two-thirds of the high-yielding farms used additional hand weeding compared with only one-third of the low-yielding farms. No weed control measures were used by about 20% of the "low" dry-seeded farms (Lantican et al 1999). This, along with the fact that "high" farms used significantly more N than the other group, may explain the yield difference between them.

In dry-seeded rice, emerging weed species are determined by such factors as cropping history, tillage practice, and past weed control measures adopted and their growth rates by the timing and intensity of rainfall in the early period of the season. In Urbiztondo, fields with prerice crops had fewer weeds than those that were fallow during the prerice season. Thus, an effective weed control strategy was to plow the field very early in the season (prerice season) and prepare the land over a longer period to remove existing weeds, and/or grow a nonrice crop before establishing dry-seeded rice (Lantican et al 1999).

Cropping intensification and farm productivity. Dry seeding enables early establishment and consequent early harvest of the wet-season rice crop. In drought-prone environments, dry seeding translates into a direct benefit in terms of a new opportunity for growing a nonrice crop after rice in areas where such an opportunity did not exist, resulting in improved soil moisture availability for the rice crop. Figure 2 indicates the relationship, under typical conditions, between planting date and water availability to mungbean, which was the popular postrice crop in Urbiztondo. The yield of postrice mungbean was closely related to soil water availability (Fig. 3). Mungbean performed significantly better after dry-seeded rice than after transplanted rice because of the earlier establishment of the crop and, consequently, better soil water availability. In 1991-93, dry seeding of rice enabled earlier planting of mungbean by 2 wk, which resulted in more than 50% higher water availability to the crop and 55% higher yield than when growing the crop after harvesting of transplanted rice. In an average year, water availability for mungbean increased by 78% when rice was harvested 20 d earlier than the average harvest date of transplanted rice, which was possible with dry seeding of rice (Saleh 1993).

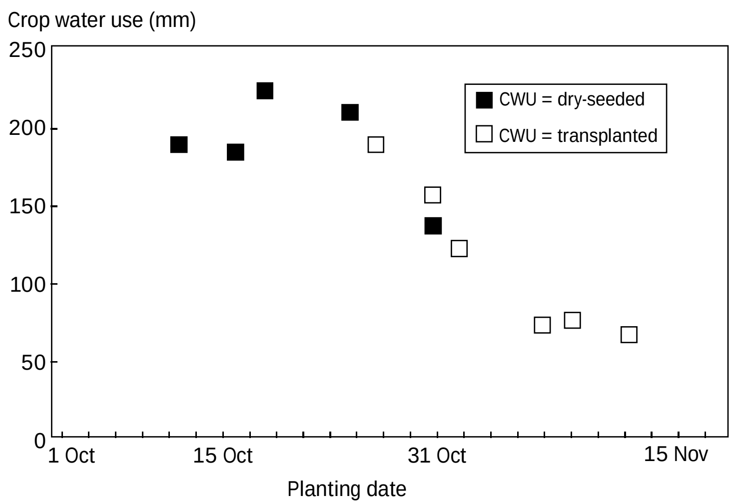

Fig. 2. Crop water use (CWU) and planting date relationship for mungbean established after dry-seeded and transplanted rice, Urbiztondo, Philippines, 1992-93 season.

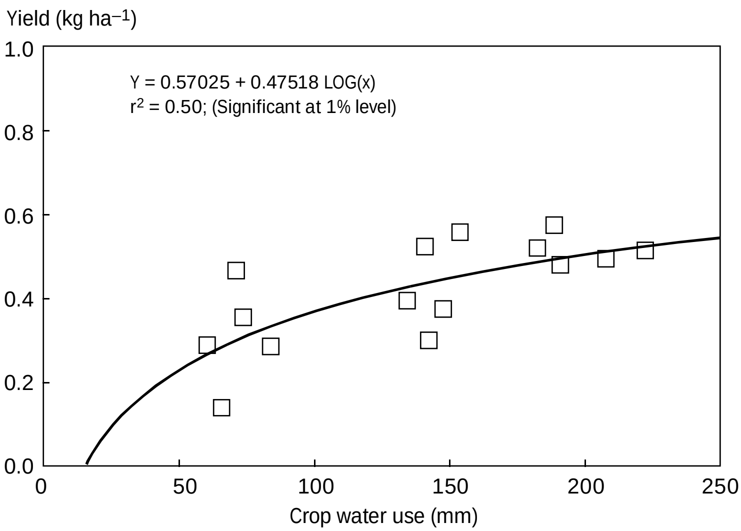

Fig. 3. Relationship between crop water use and mungbean yield, 1992-93 season.

Dry-seeded rice in Bangladesh

Although various components of direct-seeded rice have been studied for many years, the systematic investigation of its potential for drought-prone environments in Bangladesh started only recently. The IRRI-coordinated RLRRC provided special opportunities to look into direct-seeded rice-based cropping systems in drought-prone environments, where low and unevenly distributed rainfall is at the root of low productivity and poor income from farming.

The total annual rainfall in the Barind Tract of northwest Bangladesh averaged about 1,200 mm from 1989 to 2000. Its distribution is highly skewed: about 80% of the rainfall occurs during the monsoon months of June to September, leaving the postrice season very dry, especially if rice is harvested toward the end of October or later. The situation is exacerbated by 1–2-wk drought spells during the rainy season. In an average year, about 80% of the crop water requirement is available from rainfall. In 2 out of 10 years, rainfall supplies only about 50% of the total crop water requirement. The probability of at least one 10-d or 15-d drought occurring during the grain-filling period of rice is 73% and 53%, respectively (Saleh et al 2000). The probability of significant rainfall in October, when most crops are in the reproductive or grain-filling stage, is low: 63% for obtaining 50 mm or more and 48% for 75 mm or more (Manalo 1977).

Land preparation for dry seeding in June is feasible in most years since there is an 85% probability that the total rainfall in June will exceed 150 mm (Manalo 1977). This is considered adequate for completing land preparation for dry seeding of rice.

But the probability by mid-July of getting about 400 mm of rain, which is considered the minimum required for completion of wet land preparation for transplanting, is about 50% (Saleh et al 2000). Thus, once every 2 years, transplanting of rice would be delayed and subject to significant drought stress. Delayed transplanting reduces the performance of the crop because of the use of old seedlings and exposure to drought at the reproductive or grain-filling stage. The occurrence of the reproductive or grain-filling stage with the receding monsoon in late September or October is mostly responsible for the current low yields of wet-season rice in the study area. Historic data clearly show a strong positive correlation between October rainfall and rice yield (Fig. 4).

Farmers currently use transplanted wet-season (*T. aman*) rice-fallow in the high Barind Tract. For assured yields, about 75% of the farmers grow long-duration cultivar Swarna, which is photoinsensitive and matures in 140–150 d. Farmers harvest Swarna in mid- to late November and prefer it for its attractive grain color ("Swarna" in Bengali means "golden"), dark green plant type, high N responsiveness, and good market price. This cultivar has not been released nationally, however (it originated in India), and it is highly susceptible to sheath blight. Few farmers presently grow postrice crops such as chickpea, linseed, or barley, which produce low yields because of drought stress after the long-duration Swarna. The Bangladesh Rice Research Institute (BRRI), Directorate of Agricultural Extension (DAE), and nongovernment organizations such as the Center for Action Research for Barind (CARB) are therefore keen to find a viable replacement for Swarna.

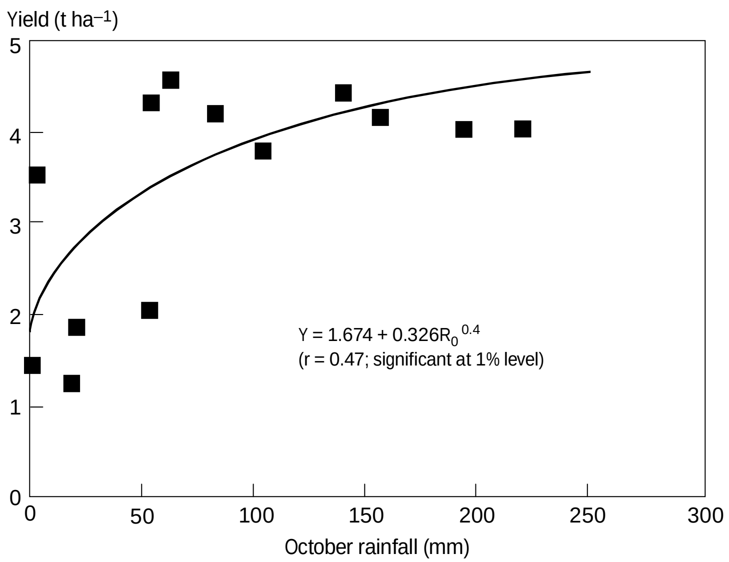

Fig. 4. Relationship between October rainfall and rice yield, Barind Tract, Rajshahi, Bangladesh.

To substantially improve productivity and farmer income, the following interventions in farmers' cropping practices were considered essential:

1. Introduction of modern rice varieties and crop establishment methods that would enable rice to be harvested earlier, with a low risk of drought stress (high and stable yields).
2. Choice of appropriate nonrice crops and cultivars, which would enable another crop to be grown profitably after rice.
3. Demonstration of the viability of this alternative rice-based cropping system.

Starting in 1994, several experiments were conducted to examine the effects of establishment method, time of sowing, and crop duration on rice yield and the consequences for the performance of subsequent *rabi* (postrice rainfed) crops.

Materials and methods

The research site is located in the Barind Tract of Rajshahi District in northwest Bangladesh (24°25′–25°10′N, 88–89°E). The Tract has a total land area of 1.6 million ha, about 90% of which is cultivated. Nearly 100,000 ha of the Barind Tract (high Barind) are purely rainfed, that is, without any irrigation facilities, and highly drought-prone. The soil is a silty loam to silty clay loam in texture, poorly drained, with a 6–8-cm thick plow pan commencing at a depth of about 10 cm below the soil surface. The soil organic matter content is low (0.8–1.2%) and the soil pH is mildly acidic (5.5–6.5).

The yield performance of selected rice cultivars established by broadcast direct seeding at 70 kg seed ha^{-1}, line sowing at 70 kg seed ha^{-1}, and dibbling at 45 kg seed ha^{-1} with a 25 × 15-cm spacing and by transplanting with 30-d-old seedlings at 25 × 15-cm spacing was examined over a range of sowing dates in 1994, 1995, and 1996. Two deep-rooted photoperiod-sensitive lines, BR4974-42-1-3 and BR4974-45-9-2, were seeded along with modern cultivar BRRIdhan 11 (BR11) and local check Bihari Bhatraj at 15-d intervals from early June to early August. For transplanting, seeds were sown in the wet bed on the same day as dry-seeded rice was sown in the field.

On the basis of findings for 2 years (1994-95), treatments were modified in 1996 and 1997. Grain yield and growth duration were examined for selected early (BRRIdhan 33 or BR33, 116–119 d), medium (BRRIdhan 32 or BR32, 125–130 d)-, and late (BR11, 140–145 d)-maturing modern cultivars that were established by either dry seeding or transplanting in different topographic conditions in 1996 and 1997. The dry-seeding method was compared with transplanting using 30-d-old seedlings for sowing from early June to early August. Chickpea (*Cicer arietinum*) cultivar BARIshola-2 (125–130 d) was sown as a dry-season crop following the harvest of late- and medium-maturing cultivars established by direct seeding and transplanting in 1996 and 1997.

The transplanting schedule for mid-July and early August was delayed for 30 and 15 d, respectively, because of a lack of rain in 1994. But, in 1995, 1996, and 1997, transplanting of 30-d-old seedlings was completed as scheduled because of timely rainfall. Blanket doses of triple superphosphate, muriate of potash, and gypsum were applied at 40-40-10 kg ha^{-1} of P_2O_5, K_2O, and S, respectively, during final land preparation. Urea at 60 kg N ha^{-1} was topdressed in three equal splits at the tillering, panicle initiation, and booting stages. Weed control was done by hand weeding at 21, 33, and 45 d after sowing or days after transplanting for all treatments. To establish chickpea, the land was plowed two to three times, followed by leveling with a board. Basal fertilizer (20-40-20 kg ha^{-1} of N-P_2O_5-K_2O) was incorporated during land preparation. For all experiments, a split-split plot design with three replications was followed, with sowing time as the main plot, cultivar as the subplot, and establishment method as the sub-subplot.

After dry seeding BR32 and BR33, seeds of chickpea (BARIshola-2) were sown in the third week of October by broadcasting. In 1996, establishment of chickpea was hampered by heavy rain after sowing (100 mm during 27-29 October), so chickpea was resown in all plots on 15 November 1996. In 1997, chickpea was sown after harvesting each rice plot, as only 3 mm of rain fell in October that year. Growth duration, yield, and yield component data of both rice and chickpea were recorded in all experiments. An analysis of variance of rice and chickpea yields and a simple economic analysis of the systems were made.

Results and discussion

Establishment method and sowing time of rice. Rice established by dry seeding in mid-June matured 7–10 d earlier than transplanted rice (Table 1). An earlier harvest gave dry-seeded rice the potential to escape the drought expected during late September to October, allowing it to perform better (Table 2). In 1994, establishment of dry-seeded rice in mid-June to early July by either broadcast or line sowing produced significantly higher grain yield than transplanted rice (Table 2), even when rainfall was minimal. Transplanting delay with older seedlings reduced yields, since less than 600 mm of rain was received, thus delaying puddling. In 1995 and 1996, however, rice establishment in mid-June by either dry seeding or transplanting produced grain yields similar to those under normal rainfall situations (Table 2). To get high yields in wet-season rice, the optimal establishment of the rice crop in the field is

Table 1. Effect of crop establishment method on growth duration of rainfed lowland rice sown in mid-June at Rajabari, Rajshahi, Bangladesh, 1996 wet season. Data are presented for three cultivars at high and medium toposequence for dry-seeding and transplanting methods of crop establishment, averaged over 2 June and 16 June plantings.

Variety	Growth duration (d)			
	High toposequence		Medium toposequence	
	DSR	TPR	DSR	TPR
BR11	139 a[a]	145 a	139 a	146 a
BR32	125 b	134 b	129 b	138 b
BR33	111 c	120 c	112 c	119 c
Mean	125	133	127	134
CV%	1.0	1.2		

[a]Within a column, means followed by a common letter do not differ significantly ($P = 0.05$).

Table 2. Effect of sowing time and crop establishment method on grain yield (t ha^{-1}) of rainfed lowland rice. Rainfed Lowland Rice Research Consortium, Rajabari, Rajshahi, Bangladesh, 1994-96.

Method of sowing rice	Time of sowing[a]				
	1 June	16 June	1 July	16 July	1 August
1994					
DS—boadcast, 70 kg ha^{-1}	–	3.1 a A	3.5 aA	3.4 aA	2.9 aA
DS—line sowing, 70 kg ha^{-1}	–	2.9 a A	3.6 aA	3.3 aA	2.0 abB
DS—line sowing, 45 kg ha^{-1}	–	3.1 a B	3.6 aB	3.5 aB	1.9 bC
TP—25 ´ 15-cm spacing	–	2.4 b A	2.8 bA	3.2 aA	1.4 cB
1995					
DS—broadcast, 70 kg ha^{-1}	2.6 a	2.8 a	2.8 a	2.5 a	–
DS—line sowing, 70 kg ha^{-1}	2.6 a	2.8 a	2.9a	2.5 a	–
DS—line sowing, 45 kg ha^{-1}	2.6 a	2.7 a	2.8 a	2.4 a	–
TP—25 ´ 15-cm spacing	2.5 a	2.4 a	2.9 a	2.4 a	–
1996					
DS—broadcast, 70 kg ha^{-1}	3.4 a	3.9 a	–	–	–
TP—25 ´ 15-cm spacing	3.4 a	3.8 a	–	–	–

[a]Within a column, means within a year followed by a common small letter or within a row followed by a common capital letter do not differ significantly (*P* = 0.05). DS = direct seeding, TP = transplanting.

Table 3. Mean yields of rice and chickpea at Rajabari, Rajshahi, Bangladesh, 1996. Data are means of 2 June and 16 June sowings for chickpea grown after dry-seeded (DS) or transplanted (TP) rice.

Cropping pattern	Grain yield of rice (t ha^{-1})		Grain yield of chickpea (t ha^{-1})		Rice equivalent yield (t ha^{-1})[a]	
	DS	TP	DS	TP	DS	TP
BR11-chickpea	4.5	4.6	1.7	1.4	10.2	9.4
BR32-chickpea	3.0	3.0	2.0	1.6	9.4	8.2
BR33-chickpea	3.5	3.0	1.9	1.6	9.7	8.2
Mean	4.0	3.6	1.9	1.5	9.8	8.6

[a]Rice equivalent yields of chickpea were calculated by using farm-gate prices of rice = Tk 5.5 kg^{-1} and of chickpea = Tk 18.00 kg^{-1}. Values are rice equivalent yields for rice followed by chickpea in each establishment method.

mid-June for dry-seeded rice and mid-July for transplanted rice. A delay in sowing could reduce yields if conditions are dry in October.

On average, from 2 and 16 June sowings, higher yield was obtained from BR11 than from photoperiod-insensitive cultivars BR32 and BR33 in 1996 (Table 3). But, at high toposequence, grain yield of BR33 was lower (Fig. 5) because of moisture stress during flowering and grain filling, with spikelet sterility of BR11 and BR33 increasing to about 40% (Fig. 6). Results in 1996 demonstrated that BR32 matured on 14 October, 12–15 d earlier than BR11 when sown in mid-June. BR33 matured on 26 September, 11–18 d earlier than BR32. Dry-seeded rice matured about 9–10 d earlier on average than transplanted rice (Table 1).

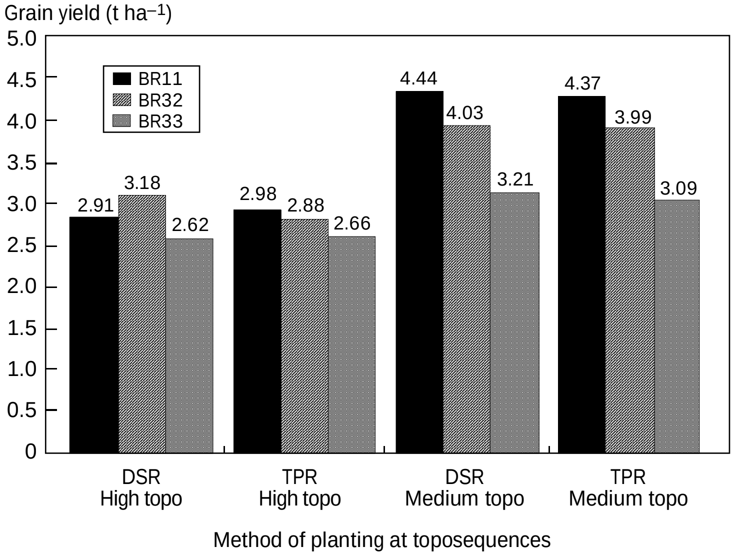

Fig. 5. Effect of rice crop establishment method on grain yield (t ha^{-1}) of rainfed aman (wet-season) rice (% CV = 10.1 for high toposequence and 11.1 for medium toposequence). DSR = dry seeding, TPR = transplanting.

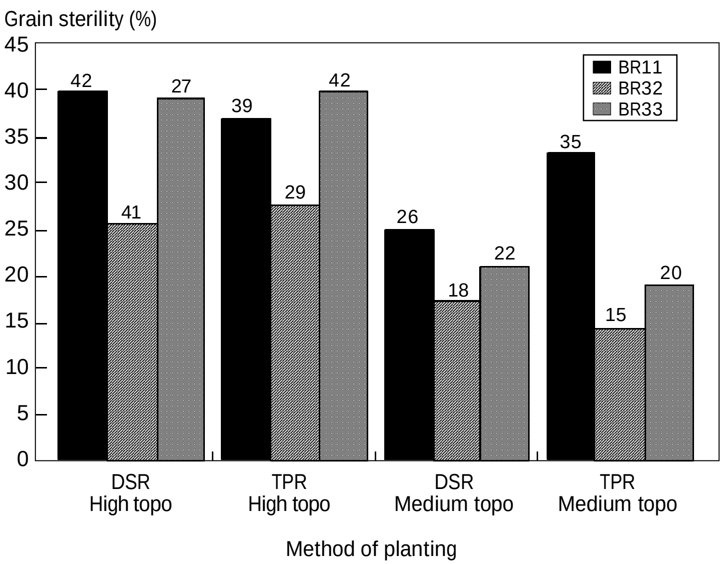

Fig. 6. Effect of crop establishment method on spikelet sterility (%) in high and medium toposequences in High Barind soil. DSR = dry seeding, TPR = transplanting.

Local farmers did not like early maturing cultivar BR33, with its coarse grains and low yield potential. Consequently, BR33 was dropped from the experiment in 1997 and replaced by BR32, a medium-maturity cultivar with an acceptable yield potential, but it suffered from serious lodging problems when high doses of N were applied. BR32 was released as a low-input type and had no lodging problem when the recommendation of 60–80 kg N ha^{-1} was followed. But farmers preferred high doses of N since they expected good responses, as was their experience with Swarna. Thus, neither BR32 nor BR33 was considered as a suitable replacement for Swarna, despite its sheath blight susceptibility. New, shorter duration, sheath blight-resistant varieties are needed, with the positive grain quality and phenotypic appearance of Swarna.

Establishment method and sowing time of chickpea. Chickpea yielded higher when sown after dry-seeded rice (Table 3). The earlier harvest of dry-seeded rice allowed chickpea to be established earlier and to perform better because of the more favorable residual soil water.

The productivity of the rice-chickpea system is better with dry-seeded BR11 than with other rice varieties tested, regardless of whether the rice was established dry-seeded or transplanted (Table 3). This is because BR11 has a longer growth duration and produces a higher yield than the other cultivars. Farmers in Rajshahi preferred getting a higher rice yield even if it meant sacrificing the yield of the subsequent crop. If BR11 or a similar variety can be established by mid-June, farmers will be able to achieve this. However, if a medium-maturity rice cultivar such as BR32 or BR33, or the more recently introduced cultivar BR39, is used, the rice-chickpea system will have greater flexibility in the choice of rice establishment method and/or the time of establishment of both crops (Mazid et al 1998).

Farmers received higher returns from the dry-seeded rice–chickpea system than from the transplanted rice-chickpea system (Table 4). The additional benefit for the dry-seeded rice–chickpea system comes from a lower production cost because of less labor used in rice, a higher rice yield, and a higher chickpea yield. Chickpea was a profitable postrice crop for Barind Tract farmers. The situation in the Philippine trials was similar, where the productivity of the rice-mungbean system was better after dry-seeded rice than after transplanted rice.

Further research needs

Better understanding of drought risk. A quantitative understanding of the drought risk to be expected during rice and nonrice crop establishment and during the reproductive and grain-filling stages of the rice crop is needed. Specifically, we lack an in-depth probabilistic interpretation of the expected drought risk at various times, especially during the beginning and end of the monsoon. We need to assess the risk for alternative methods of crop establishment and to determine the time leverage that farmers have in using these methods. Likewise, to grow profitable postrice crops, we need detailed analyses of soil moisture retention properties to assess the prospects for crop maturation on stored soil water reserves.

Table 4. Cost and return of rice established as transplanted (TPR) and dry-seeded (DSR) rice crops and a subsequent chickpea crop, Barind Tract, Rajshahi, Bangladesh, 1999.

Items	Rice		Chickpea	
	TPR plot (Tk ha^{-1})[a]	DSR plot (Tk ha^{-1})	TPR plot (Tk ha^{-1})	DSR plot (Tk ha^{-1})
Human labor	9,854	8,288	3,025	3,300
Animal labor	5,017	4,500	800	800
Power tiller	1,444	–	–	–
Seed	588	663	1,350	1,400
Fertilizer	3,653	3,847	300	450
Manure	1,609	2,063	–	–
Insecticide	176	200	–	–
Total cost of production	22,341	19,561	5,475	5,950
Yield (t ha^{-1})	4.4	4.7	1.0	1.1
Gross return	36,827	38,127	25,125	28,000
Net return	14,486	18,566	19,650	22,050
Benefit-cost ratio	1.64	1.94	4.59	4.71
Unit cost of production (Tk kg^{-1})	5.12	4.20	5.45	5.31

[a]US$1 = Tk 49.

Weed species composition and management. There is a genuine concern that replacing transplanted rice with dry-seeded rice will result in weed species shifts, with an increase in competitive grass weeds. The nature of these changes and their effect on farming practices as well as their long-term consequences for management must be adequately understood. In transplanted rice, effective weed control is generally possible using manual, mechanical, or manual-mechanical methods. In dry-seeded rice, not only is a greater diversity of weed species to be expected, but the need to achieve early season control may place greater reliance on chemical means of weed control, as has happened in other countries. In Bangladesh, the availability and use of suitable herbicides remain very limited. The cost-effectiveness of herbicide use must be adequately studied and appropriate regulatory mechanisms must be put in place to ensure correct usage.

Soil enrichment potential of chickpea. As a legume, chickpea grown after rice is expected to enrich the soil with nutrients, especially nitrogen. The extent of N fixed in the soil by the chickpea and its availability to the succeeding dry-seeded rice crop should be quantified and the economic implications of this process should be adequately assessed.

Pest and disease problems of chickpea. Unfortunately, if chickpea is grown at a site for several years, disease problems may increase, especially for root rots such as *Botrytis* sp., which possesses long-living sclerotia in the soil. Crop rotation with other postrice crops such as linseed or mustard may be essential to keep root rot damage to chickpea down to acceptable levels. Likewise, *Helicoverpa armigera* may increase in prevalence during grain filling of chickpea and linseed. Pest and disease management will be essential for crop protection.

Wide-scale adoption of the rice-chickpea system. It is impractical to expect that all relevant issues will be adequately answered before recommendations are made and field activities are conducted to popularize these promising technologies based on dry-seeded rice. Experimental results in the Barind area of Rajshahi have shown the potential of the dry-seeded rice–chickpea system from both technical and economic viewpoints. Wide-scale demonstrations, involving extension people and NGOs that are committed to improving the livelihoods of farming communities in the area, should be conducted. Disseminating information on new, improved practices and materials (e.g., seeds, herbicides) and demonstrating the essential components of the new technology to farmers should be given priority. Financial support should be forthcoming for such a worthwhile activity. A sound database of farming practices and economics should be established for the Barind Tract area so that the impact of new technologies can be quantitatively evaluated in the future.

Conclusions

The two rainfed drought-prone environments, Rajshahi in Bangladesh and Urbiztondo in the Philippines, have many similarities, such as seasonal drought, farmers' cropping practices, and management options that farmers could consider. Several years of empirical research and farmer surveys have generated a significant body of useful knowledge on alternative crop establishment methods at the two sites. At both sites, when rainfall is early and adequate, both dry-seeded rice and transplanted rice will produce about the same yield. But it is the lower labor cost of dry-seeded rice and the higher productivity of the postrice crop (mungbean in Urbiztondo and chickpea in the Barind area) that make dry-seeded rice a more practical option. In the Barind area, chickpea can be grown successfully after long-duration varieties such as BR11 (or BR31) if it is dry-seeded by mid-June. BR31 may be an acceptable substitute for the popularly grown but disease-susceptible Swarna because both have similar yield potentials.

As drought prevails at early tillering or at the reproductive stage in areas such as the Barind Tract in Bangladesh and Urbiztondo in the Philippines, we need to generate more in-depth understanding of the phenomenon that could clearly depict the cropping options available to farmers along with their risks and advantages for the given environments. The application of modeling techniques using long-term field-based data can help generate such information. Further research should be done to quantitatively analyze drought risk.

The rice varieties that farmers now use for dry seeding were developed for transplanting in irrigated environments. These are generally well suited for favorable rainfed conditions, but their performance has not been optimal in drought-prone environments. Early maturing, high-yielding rice varieties that can withstand drought and suppress weed growth (through vigorous vegetative growth of the rice plant at the early stage) are badly needed to enable the dry-seeded rice system to perform better.

As dry land preparation is often necessary for dry seeding, plowing with bullocks is difficult. In many areas, the lack of access to machinery impedes farmer adoption of the technology.

Because farmers may hesitate to change their current practices and they lack clear examples to follow, practical demonstrations of the functionality and benefits of dry-seeded rice-based cropping systems should assist the development and dissemination of technologies where genuine prospects exist. The increasing popularity of dry-seeded rice systems in Urbiztondo in the Philippines shows the potential power of such demonstrations. In addition, scientists can gain from feedback from farmer experiences in adapting and adopting the technologies. Studies to monitor the adoption process, capture feedback, and document impact are needed.

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Notes

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Direct-seeding and reduced-tillage options in the rice-wheat systems of the Indo-Gangetic Plains of South Asia

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With the introduction of new, improved shorter duration wheat and rice varieties in South Asia in the mid-1960s, double cropping of these two cereals became possible. Rice is grown in the wet, monsoon summer months and wheat follows in the dry, cool winter in one calendar year. More than 12 million ha are grown to rice and wheat in Bangladesh, India, Nepal, and Pakistan. Another 10 million ha are grown in China. This rice-wheat system is one of the most important cropping systems for cereal production and food security in the region.

Most of the rice in this system is managed by transplanting rice seedlings into puddled soils. This age-old method of planting is used to reduce water percolation. It also helps control weeds. But puddling also degrades the soil physical condition with resulting difficulties in establishing and growing succeeding upland crops such as wheat. Much of the research in the region looks at the possibility of establishing rice without puddling. Major perceived hurdles include the inability to economically control weeds and increased water use. However, there are situations when water tables are high or soils are fine-textured where puddling is not needed to slow water infiltration and where dry-seeding technology may work. Less research has been done on evaluating this technology on a systems basis.

This paper presents data from experiments conducted at Pantnagar University in India and at the Nepal Agricultural Research Council (NARC) Bhairahawa Wheat Research Center in the *tarai* region. Experiments looked at the effects of various tillage and crop establishment practices on the productivity of both rice and wheat. At both sites, rice yield was not adversely affected by direct seeding without puddling and, in Nepal, it was not affected by deep tillage before establishment. Direct seeding led to greater weed pressure at Pantnagar but not at Bhairahawa. Crop damage from brown planthopper was higher in direct-seeded plots in one year at

Pantnagar. Rice yield attributes were altered by direct seeding, indicating a need to optimize plant density and spacing parameters for this practice. At Pantnagar, soil bulk densities were lowered and infiltration rates increased without puddling. This led to a different water management regime for direct-seeded rice and provided a better soil physical condition for the succeeding wheat crop.

Wheat yields were affected by various tillage options whether applied in the rice season or in the wheat season. Wheat yields were significantly higher when rice soils were not puddled. At Pantnagar, zero tillage did not do as well as conventional tillage but this may have been because of insufficient moisture for good root development in zero-till plots. At Bhairahawa, the reverse was true, especially in 1997-98, when wet conditions caused a delay in planting in the treatment with tillage. Here, significant interactions were also observed between rice and wheat tillage and establishment practices. The best wheat yield was obtained when soil was deep-tilled and unpuddled for rice and not tilled for wheat (surface-seeded). The lowest yield was obtained when surface-seeded wheat followed conventional tillage and puddling for rice. Although rice yields were higher than wheat yields, differences in the latter were most important for overall system productivity. This paper suggests that direct-seeded rice on unpuddled soils is feasible and that zero-till wheat following unpuddled rice soils is cost-effective, conserves resources, and does not reduce yield.

Rice-wheat is a major cropping system in India, Pakistan, Bangladesh, and Nepal, grown on approximately 12 million ha of land. The two crops are grown in sequence in one calendar year, with rice during the wet rainy season and wheat during the relatively dry and cool winters. With the introduction of new high-yielding rice and wheat varieties in the 1960s, double cropping of these two crops became feasible. Area and productivity under the two crops have increased since then (Hobbs and Morris 1996).

In high-productivity irrigated areas, rice is transplanted after puddling the fields (plowing when fields are saturated). Puddling is done for easier transplanting and to reduce water infiltration. It destroys the soil physical structure, which has implications for the following wheat crop. In this method, fields are kept flooded most of the time, thus requiring large quantities of water. This creates hydraulic imbalances and lowers the water table in some areas, while causing increases in water table depth and waterlogging and associated salinity/sodicity in others (Harrington et al 1993b). However, puddling and keeping fields flooded also help control weeds.

Rice transplanting requires a large amount of labor, usually at a critical time for labor availability, which often results in shortages and increasing labor costs. In addition, under the changing socioeconomic environment in South Asia, workers (especially younger male workers) are not available or are reluctant to undertake tedious agricultural operations such as transplanting. These situations also produce labor shortages and further escalate labor costs. Alternate methods of establishing crops, especially rice, that require less labor and water without sacrificing productivity are needed. Pandey and Velasco (this volume), considering water availability and opportunity cost of labor, have hypothesized that dry seeding of rice is an appropriate alternative for South Asia.

Surveys have shown that sowing of wheat after rice is often delayed because of the number of tillage operations needed for good seedbed preparation. As a result, costs escalate and farmer profit margins decrease (Hobbs et al 1992, Harrington et al 1993a). Many studies have shown that any delay in wheat planting after November results in a linear decline in yield potential (Randhawa et al 1981, Ortiz-Monasterio et al 1994). Finding ways to reduce the traditional practice of repeated tillage operations prior to wheat sowing is an important research area. Aslam et al (1993) have shown that zero-tillage establishment of wheat after rice gives equal or even better yields than when wheat is planted after normal tillage. The extra yield is associated with timely planting. Further studies in various institutions in South Asia with zero-tillage establishment of wheat on several different soil types using different methods suited to different socioeconomic conditions also confirm that tillage can be reduced when establishing the wheat crop after rice (Hobbs et al 1997). A few studies have examined the effect of different rice establishment methods combined with different wheat establishment methods on total system productivity. This paper presents the results from three of these systems-based experiments with the view to finding solutions to the problem of labor scarcity, water needs, and productivity of rice-wheat systems.

Materials and methods

Experiments were carried out at G.B. Pant University of Agriculture and Technology, Pantnagar, India, and at the Nepal Agricultural Research Council (NARC) Wheat Research Station, Bhairahawa, in the *tarai* region of Nepal.

Pantnagar

The experiment on the University farm at Pantnagar began in 1993 at two sites differing in soil texture (silt-loam and sandy-loam). The characteristics of the two soils are given in Table 1.

The experimental treatments included two methods of rice establishment: (1) direct seeding on nonpuddled soils (DSR) and (2) transplanting on puddled soils (TPR).

These two rice establishment plots were divided into two after the rice harvest and each half was planted with wheat as follows: (1) wheat sowing by zero tillage (ZT) and (2) wheat sowing by conventional tillage (CT).

This resulted in four treatment combinations that were replicated five times in a split-plot design. The plot size for rice was 10 × 20 m. In wheat, rice plots were split into two, leaving an area of 10 × 10 m for each wheat treatment. The trial on the silty loam soil was conducted for 3 y from 1993 to 1996, whereas the one on light-textured soil has continued with some modifications for 6 y.

Table 1. Soil characteristics of three sites at the onset of experiments, G.B. Pant University, India, and Bhairahawa, Nepal.

Soil characteristics	GB Pant site 1	GB Pant site 2	Bhairahawa site
Texture	Silty loam	Sandy loam	Silty clay loam
Bulk density (Mg m^{-3})	1.39	1.29	1.60
pH	7.5	7.0	7.8
Organic matter (%)	2.25	2.15	1.60
CEC (meq 100 g^{-1} soil)	23.6	18.9	na[a]
Total N (%)	0.11	0.10	0.08
Available P (Olsen) (ppm)	43.1	30.0	7.5
Available K (kg ha^{-1})	277	245	65

[a]na = not applicable.

Direct-seeded rice plots were prepared by harrowing and were seeded by hand in rows at about mid-June. On the same day, rice was sown separately in a nursery for transplanting 25 d later. Before transplanting, plots were flooded and puddling was done with a tractor puddler. After puddling, seedlings were transplanted at 20 × 15-cm row spacing. Standing water (3–5 cm) was maintained until grain-setting in TPR plots, whereas soil was maintained near saturation in DSR plots. Appropriate pest control measures were used in both treatments including weed control by herbicide (butachlor) and by hand. Wheat was sown directly with a Pantnagar zero-till drill in ZT plots. This is a simple wheat drill made in India in which the soil openers are adapted for planting without tillage. In CT plots, land was prepared with five to six harrowing operations and then wheat was drilled. Planting of ZT and CT plots was done on the same day rather than at optimal soil moisture for each treatment. Uniform crop management practices were followed in the two treatments.

Yield and yield attributes of each crop were measured. Soil bulk density and hydraulic conductivity were measured on cores collected from the 0–7- and 12–19-cm depths. In the silty loam soil, data were collected in the 1993-94 rice and wheat seasons. Observations were made in the rice season 20 d after transplanting (20 DAT) and after harvest, whereas, in the following wheat season, these were recorded at the crown root initiation (CRI) stage (21 d after wheat sowing) and at harvest. At the end of the trial in 1996, after the wheat harvest, observations were recorded again. In the sandy loam soil, physical properties of the surface soil were recorded in the wheat crop at the CRI stage during 1996-97, 4 years after the same treatments were kept in fixed plots. Infiltration rates were also recorded at the same time the bulk density and hydraulic conductivity were taken although readings were not plotted against time to determine a steady-state value.

Bhairahawa

The experiment in Nepal began in the 1997 rice season on a silty clay-loam soil and is continuing as a long-term experiment. This experiment also has direct-seeded unpuddled (DSR) and transplanted puddled (TPR) rice treatments. It has an additional deep-tillage (DT) treatment, which was done with a single tine subsoiler to a depth of 45 cm before the rice crop in half of both rice establishment systems and was compared with the other half with no deep tillage (NT). This resulted in four strips as main plots for each of these combinations: DT-DSR, DT-TPR, NT-DSR, and NT-TPR. In the wheat season, each main plot in the rice season was split in half and wheat was planted by either surface seeding (SS) (seeds broadcast directly onto a saturated soil surface) or with a single pass of a seeder-cum-rotovator attached to a 12-hp Chinese hand tractor (CHT). The experiment was a split-plot design with three replications. The main plots were deep tillage and rice establishment and wheat planting was the subplot. Plot size was 10 × 20 m for each individual treatment. In neither Pantnagar nor Bhairahawa was rice direct-seeded on puddled soils or transplanted on unpuddled soils.

The DSR treatment was planted with the seed drill attached to the CHT. The TPR treatment was managed in the same way as the Pantnagar experiments with the seedbeds seeded on the same day the direct-seeded rice was planted. Surface seeding of wheat was done immediately after the rice harvest onto saturated soil with seed soaked for 12 h. Irrigation was provided, if needed, to obtain the correct surface moisture. CHT seeding was done as soon as the soil moisture level was suitable. It was 42 d later than SS in 1997 because of wet soil, and 15 d later than SS in 1998.

In addition to yield and yield component data, weed biomass and the effect of weeds on crop yields were measured in the 1997 rice season. Weeds were estimated from duplicate quarter-meter-square quadrats within an unweeded 2-m strip across one end of the plots. Root biomass was estimated in the 1997-98 wheat season after washing roots from soil cores taken from 0–15-cm and 15–30-cm depths.

Results

Rice crop

Table 2 shows a summary of the rice and wheat yields for all sites averaged across years. The data show that the transplanted and direct-seeded crops were similar at all sites. The transplanted crop had higher yields only in silt-loam (site 1) at Pantnagar in 1995 and in the second sandy loam site in 1994. In these years, the brown planthopper (BPH) population in the DSR crop was higher than in the transplanted rice plots. More than 50% of the area in the DSR crop was damaged by the leafhopper (BPH) compared

Table 2. A summary of yield[a] of rice and wheat across three sites, with and without puddling.

Location	Treatment	Yield ($t\ ha^{-1}$)		
		Rice	Wheat	Total
GB Pant 1	Puddled	6.1 a	4.1 b	10.2 a
	Unpuddled	5.6 a	4.6 a	10.2 a
GB Pant 2	Puddled	5.6 a	3.9 a	9.5 a
	Unpuddled	5.3 a	4.0 a	9.3 a
Bhairahawa	Puddled	5.3 a	3.1 b	8.4 b
	Unpuddled	5.4 a	3.4 a	8.8 b

[a]Numbers followed by the same letter are not significant using Duncan's multiple range test.

with only 5% in the TPR crop. Damage appeared later in the TPR crop, which was physiologically younger than the DSR crop by an estimated 20 d. The closed canopy under direct seeding provided favorable conditions for the multiplication of BPH. When this insect was not prevalent, yields were on a par in both treatments at all three sites.

During both years of the Bhairahawa experiment, rice yields were similar across all treatments (Table 2). Deep tillage or puddling had no effect on rice yields in either year. However, weed flora appeared to shift as a result of the rice tillage/puddling treatments. In 1997, weed population variability was high and land preparation method had no significant effect on weed counts. By 1998, nonpuddled soils had more grasses and broadleaf weeds, whereas puddled soils had more sedges (data not shown).

The yield attributes of the rice crop at the G.B. Pant site show that panicle number per unit area was almost 150% higher in the DSR crop than in the TPR crop, but grain weight per panicle was higher in the TPR crop (Table 3). The 1,000-grain weight was the same for the two treatments. This compensation of various yield components resulted in statistically similar grain yields. Similar observations were found at the other two sites.

Wheat crop

Yield data for wheat following puddled or unpuddled soils averaged across all years are also shown in Table 2. Wheat yield was significantly higher in plots where soils were not puddled in Pantnagar (silty loam) and Bhairahawa (silty clay-loam) and not different in the coarser Pantnagar soil. Yield advantage varied from 9% to 14% in different years at Pantnagar site 1 and was 10% at Bhairahawa. The main yield component responsible for this was spikes m^{-2}, which was greater in unpuddled treatments at both locations. Thousand-grain weight and grains per spike were similar.

Tillage practices for sowing wheat did not make a difference in the two Pantnagar experiments when averaged over all years, but they did make a difference at the Bhairahawa site in the first year (Table 4). Since both treatments were planted on the same day, no yield difference between these treatments is expected. However, there were some differences between years (data not shown). In drier years, such as 1994, the zero-till treatment did significantly worse than normally tilled plots, but in wet years such as 1997, it performed better. The two methods of wheat tillage, zero and

Table 3. Yield attributes of rice crops under two methods of crop establishment at site 1 (silty loam soil), Pantnagar, India.

Treatment	Panicles m^{-2} (no.)		Grain weight $panicle^{-1}$ (g)		1,000-grain weight (g)	
	1993	1994	1993	1994	1993	1994
Transplanted	243	247	2.6	2.7	29.5	29.9
Direct-seeded	355	365	1.6	1.9	29.3	29.3
CD (5%)	25	21	0.4	0.2	ns[a]	ns

[a]ns = not significant.

Table 4. Summary of wheat yields[a] at all sites following zero tillage or normal tillage.

Location	Treatment	Wheat yield (t ha^{-1})
GB Pant site 1	Zero tillage	4.3 a
	Normal tillage	4.7 a
GB Pant site 2	Zero tillage	3.9 a
	Normal tillage	3.9 a
Bhairahawa site	Zero tillage	3.7 a
	Normal tillage	2.8 b

[a]Numbers followed by the same letter are not significant by Duncan's multiple range test.

conventional, at the second sandier Pantnagar site did not result in any yield difference in 4 out of 6 years (data not shown). However, in one year, 1994-95, low soil moisture resulted in less germination and lower yield in the zero-till treatment. In contrast, productivity in zero-till plots was higher in 1997-98 because of high soil moisture at planting. Good seedbeds could not be prepared in conventional-tillage plots because of higher moisture and limited time available for tillage. This suggests that zero tillage is equal to conventional tillage on this soil type when planted on the same day. But soil moisture at planting is critical and zero tillage can do better if the correct soil moisture level is present at planting. Zero tillage needs higher soil moisture at planting than normally tilled plots.

The same was observed at Bhairahawa. In 1997, there was so much rain that only the zero-till plot could be planted on time. The normally tilled plot was planted almost a month later, with significantly lower yields. In 1998, treatments did not differ when planting dates were similar.

Total rice plus wheat production

Table 2 shows total rice and wheat production. There were no differences in total grain yield per year in any of the locations irrespective of treatment, such as puddled or unpuddled combined with tillage or no tillage for wheat. Total rice-wheat production was just under 1 t higher in finer textured Pantnagar soil than in the coarser textured soil. The Bhairahawa site had the lowest total production but this was because less nitrogen was used (100 kg N vs 120 kg N in both crops).

Tillage interactions at the Bhairahawa site

The Bhairahawa data show interesting interactions (Fig. 1). Two-way interactions between tillage (deep vs normal) and puddling (DSR vs TPR) as well as puddling (DSR vs TPR) and wheat planting method (SS vs CHT) were significant in 1998-99 at P levels of 0.10 and 0.05, respectively (Fig. 1). Deep tillage negated the adverse effect of puddling on the next wheat crop. Shallow tillage and puddled soil resulted in lower wheat yields compared with unpuddled plots. Likewise, there were no differences in wheat yield between puddled or unpuddled soils when CHT was used, but there was a significant difference in yield between puddled and unpuddled soils when the crop

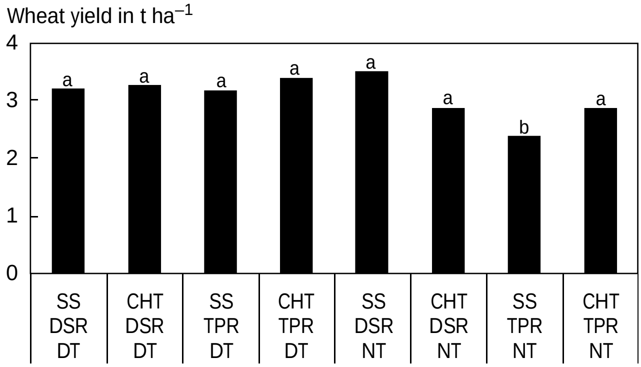

Fig. 1. Wheat response to tillage options in the 1998-99 season in Nepal (three-way interaction). SS = surface seeding, CHT = Chinese hand tractor, DSR = direct-seeded rice, TPR = transplanted rice, DT = deep tillage, NT = no deep tillage. Wheat yields with the same letters above the columns are statistically not significantly different from each other at the 5% level of significance.

was surface-seeded (zero tillage). Surface seeding was the best treatment when soils were not puddled and the worst when they were puddled. The main yield component responsible for this effect was tiller number.

Some differences in wheat rooting were noted from these experiments (data not shown). During the 1997-98 season, unpuddled treatments had significantly more roots ($P = 0.10$) in the 0–15-cm depth than puddled soils. CHT treatments had the same dry root mass as SS in the 0–15-cm depth but more in the lower layer. However, these data need more attention in future cycles of this experiment.

Pantnagar soil physical data

Site 1 (silty loam soil). Puddling for transplanting increased bulk density in surface soil early in the crop season (20 DAT) compared with unpuddled plots for direct seeding. At harvest, soil in puddled plots was more compact in both surface and subsurface layers (Table 5). Puddling considerably reduced hydraulic conductivity and infiltration rate throughout the rice season. At the rice harvest, the infiltration rate in puddled plots was half that of plots where soil was not puddled.

In the wheat season, the effect of puddling persisted in the surface soil where bulk density was significantly lower in unpuddled plots (average of zero-till and normal plots) compared with puddled plots where rice was transplanted (Table 6). Hydraulic conductivity and infiltration were higher in unpuddled plots. Tillage practices for wheat sowing had a marked effect on soil properties. Tillage (normal tillage, average of puddled and unpuddled plots) reduced bulk density and enhanced hydraulic conductivity and infiltration compared with zero tillage.

After 3 years of continuous rice-wheat cropping, bulk density was less in unpuddled plots and particularly where soil was tilled for wheat (Table 7). Bulk density of subsurface soil was quite high in all plots (1.67–1.74 Mg m^{-3}). Hydraulic conductivity and

Table 5. Effect of rice planting method on physical properties of surface and subsurface soils during the rice season (1993), site 1 (silty clay), Pantnagar.

Treatments	Bulk density ($Mg\ m^{-3}$)				Hydraulic conductivity ($mm\ h^{-1}$)				Infiltration rate ($mm\ h^{-1}$)	
	Surface layer (0–7 cm)		Subsurface layer (12–19 cm)		Surface layer (0–7 cm)		Subsurface layer (12–19 cm)			
	20 DAT[a]	Harvest[b]	20 DAT	Harvest	20 DAT	Harvest	20 DAT	Harvest	20 DAT	Harvest
Direct seeding	1.41	1.43	1.61	1.64	3.24	2.17	1.40	1.84	0.75	1.81
Transplanting	1.53	1.50	1.58	1.70	0.57	1.03	0.43	1.16	0.44	0.92
CD 5%	0.05	0.03	ns	0.05	0.04	0.05	0.05	0.11	0.07	0.03

[a]20 DAT = observations 20 d after transplanting. [b]Harvest = observations recorded after rice harvesting. ns = not significant.

Table 6. Effect of rice planting method and tillage wheat sowing on soil physical properties during wheat season (1993-94), site 1 (silty clay), Pantnagar.

Treatments	Bulk density ($Mg\ m^{-3}$)				Hydraulic conductivity ($mm\ h^{-1}$)				Infiltration rate ($mm\ h^{-1}$)	
	Surface layer (0–7 cm)		Subsurface layer (12–19 cm)		Surface layer (0–7 cm)		Subsurface layer (12–19 cm)			
	CRI[a]	Harvest[b]	CRI	Harvest	CRI	Harvest	CRI	Harvest	CRI	Harvest
Tillage for rice										
Direct seeding	1.39	1.44	1.63	1.64	2.83	2.87	2.42	2.19	2.34	2.14
Transplanting	1.45	1.49	1.65	1.69	2.21	2.03	1.91	1.63	1.84	1.55
CD 5%	0.04	0.02	ns	ns	0.20	0.28	0.16	0.15	0.13	0.06
Tillage for wheat										
Zero	1.46	1.54	1.65	1.68	1.92	2.00	1.34	1.38	1.31	1.31
Conventional	1.38	1.44	1.62	1.65	3.12	2.90	2.99	2.44	2.86	2.37
CD 5%	0.02	0.04	0.03	0.02	0.30	0.21	0.13	0.13	0.11	0.06

[a]CRI = observation recorded at crown root initiation stage of wheat. [b]Harvest = observations recorded at wheat harvest.

Table 7. Soil physical properties under different tillage practices in surface and subsurface soil (9 May 1996 after wheat harvest), site 1 (silty loam), Pantnagar.[a]

Treatment		Bulk density ($Mg\ m^{-3}$) in soil depth of		Hydraulic conductivity ($mm\ h^{-1}$) in soil depth of		Infiltration rate ($mm\ h^{-1}$)
Rice	Wheat	0–7 cm	12–19 cm	0–7 cm	12–19 cm	
DS	ZT	1.49a	1.70 a	2.08 b	1.48 b	1.40 b
DS	CT	1.43 b	1.67 a	3.08 a	2.47 a	2.35 a
TR	ZT	1.54 a	1.74 a	1.76 b	1.29 b	1.23 b
TR	CT	1.46 b	1.69 a	2.44 a	2.01 a	1.92 a

[a]Numbers followed by the same letter are not significant by Duncan's multiple range test. DS = direct seeding, TR = transplanting, ZT = zero tillage, CT = conventional tillage.

Table 8. Soil physical conditions in surface soil (0–15 cm) under different tillage practices at the crown root initiation stage of wheat (1996-97), site 2 (sandy loam), Pantnagar.[a]

Treatment	Bulk density ($Mg\ m^{-3}$)		Hydraulic conductivity ($mm\ h^{-1}$)		Infiltration rate ($mm\ h^{-1}$)	
	ZT	CT	ZT	CT	ZT	CT
Direct seeding	1.45 a	1.35 a	3.10 a	4.55 a	3.70 a	6.57 a
Transplanting	1.50 b	1.40 b	2.55 b	3.60 b	2.45 b	3.60 b

[a]Numbers followed by the same letter are not significant by Duncan's multiple range test. ZT = zero tillage in wheat, CT = conventional tillage in wheat.

infiltration rate were higher in plots where soil was not puddled. Tillage for wheat sowing (CT) considerably increased both hydraulic conductivity and infiltration rate. However, this was not steady-state infiltration.

Site 2 (sandy loam soil). Physical properties of the surface soil were recorded at the CRI stage of the 1996-97 wheat crop in this trial. Similar to results of the silt-loam soil trial, bulk density was lower and hydraulic conductivity and infiltration rate were higher in plots where soil was not puddled (Table 8).

Discussion

The rice crop in both India and Nepal was established by two methods—direct dry seeding on unpuddled soils and transplanting on puddled soils. Experiments were conducted on three different soils varying considerably in texture, bulk density, hydraulic conductivity, infiltration rate, and cation exchange capacity. Yet, on all three soils, the productivity of dry-seeded rice was the same as that of the transplanted crop, except for one year at Pantnagar, where brown planthopper incidence was higher in the direct-seeded crop. Factors that could have contributed to increased insect pressure with direct seeding include a denser crop canopy, which creates a moister microenvironment, and a more advanced stage of crop development. If the latter factor is involved, it may be considered an experimental artifact. In any event, future research should investigate whether reduced seeding rate or increased spacing would reduce insect pressure in direct-seeded rice. Alternatively, resistant germplasm can be sought since the use of insecticides is being discouraged.

Variations in crop growth parameters were observed at Pantnagar, with more panicles per unit area in the direct-seeded crop but higher grain weight per panicle in the transplanted crop. Lower panicle number in the transplanted crop was compensated by higher grain weight per panicle so that yields were similar. There is a possibility that yields of direct-seeded rice could be increased through higher nutrient use to allow more grains to develop per panicle. This needs further study to examine interactions with pest populations and lodging.

More weed growth was observed early in the direct-seeded unpuddled crop than in the puddled treatment, in which higher infiltration rates made it more difficult to maintain standing water, which helps check weed growth. However, yields were not affected because herbicides and some hand weeding controlled weeds. In Nepal, there were no differences in weed counts between puddled and unpuddled soils, but there was a shift in weed species in the second year with sedges becoming more prevalent in puddled soils. Further study of weed populations and dynamics is needed in these and other tillage experiments. Weeds may become less of a problem in unpuddled soils if they are continually controlled and the seed bank becomes exhausted.

Mulching of both rice and wheat is an old technology that may benefit the rice-wheat system. The impact of mulching on weed pressure in direct-seeded rice is an important research area and mulching may be a solution to weed problems in direct-seeded, unpuddled rice culture. In China, which has recently shifted to zero-till establishment of wheat after rice, mulching with rice straw also plays an important role in the success of this reduced-tillage technology. The mulch helps to maintain optimal surface soil moisture for germination and rooting, protects the seed from birds, and helps control weeds (Guo Shaozheng et al 1995). But researchers noted that, after 3 to 4 years, the soil must be deeply plowed to control weeds. These aspects need further investigation over long time frames to ensure that cumulative effects of treatments are properly evaluated.

Data show that dry-seeded rice is viable in the three locations studied. It could also considerably save on labor. According to various estimates, direct seeding can reduce labor requirements by as much as 50% (Isvilanonda 1990, Fujisaka et al 1993, Singh et al 1994, Pandey et al 1995, 1998, Pandey and Velasco 1998). Direct seeding can also reduce production risk when the crop is sown with premonsoon rains, thus avoiding potential variability in rainfall at planting. There is sufficient time between the wheat harvest and rice sowing to allow direct seeding in India and Nepal. This is not the case in China's Yangtze River valley, where rice must be transplanted to save the extra field days needed by direct-seeded rice. This partly explains why the Chinese are not experimenting with direct-seeded rice in these areas. In South Asia, there are areas in the eastern Gangetic Plains where two rice crops and one wheat crop are grown in the same year. In these situations, direct-seeded rice would not be a viable option because of constraints in field time. Unfortunately, estimates of production costs for the various treatments have not yet been made.

Soil management practices associated with the two methods of rice establishment created variations in soil physical properties at Pantnagar. At the rice harvest, the bulk density of surface and subsurface soil was higher, whereas hydraulic conductivity and infiltration rate were lower in puddled plots than in unpuddled plots. This led to different water management strategies for rice, in which soils in direct-seeded plots were maintained under near saturation rather than flooded. An analysis of total water use in both treatments is needed to determine which system requires more water. Such research requires the creation of hydrologically isolated plots and precise measurement of water inputs, including that needed for raising the nursery. A key question for areas with water shortage is whether a crop of dry-seeded rice can be grown with less water without reducing yield.

Puddling of soil for rice adversely affected the following wheat crop in heavier textured soils but not in lighter textured soil (sandy loam). Wheat productivity was

13% higher in unpuddled treatments on silt-loam soil at Pantnagar and 8% higher on silty clay-loam soil at Bhairahawa. Measurements of soil physical properties showed that light-textured soil was still quite open with relatively high hydraulic conductivity and infiltration rate even in puddled plots.

The best tillage option for wheat also varied with soil type. Because the soil is not tilled in zero tillage, soil strength is higher and rooting is more difficult. Increasing soil moisture overcomes this problem by reducing soil strength and making rooting easier. This is one of the problems of the Pantnagar experiments. In this type of experiment, both tillage treatments for wheat should be planted at optimal moisture if not planted on the same date. This means that zero tillage should be practiced when soils are wetter than they normally are in conventionally tilled plots. At Pantnagar, wheat in both establishment treatments was planted on the same day at a soil moisture content that was optimal for normal tillage but probably too low for zero tillage. The soil was probably too dry, thus impeding root development in zero-tillage treatments, with resulting poor rooting and tillering. In the Nepal experiment, zero-tillage planting by surface seeding was done at optimal soil moisture for this practice. The treatment with tillage (CHT) was planted later when the soil was drier. In these experiments, zero tillage did better than the CHT treatment in the first year (because of much earlier planting), but they were equivalent in the second year when planting dates were closer. With lighter textured soils, irrigation is often needed just before or just after seeding to help germination and reduce soil strength for rooting in zero-tillage treatments.

The Nepal experiment gives further insights into the effect of tillage interactions on system productivity. Deep tillage was beneficial for the wheat crop by the second year of this experiment, although additional data are needed to confirm this observation. Deep tillage negated the harmful effect of puddling even though it was done before the puddling for the preceding rice crop. The zero-tillage treatment produced both the best and worst yields in wheat; the best when it followed deep tillage and no puddling for rice, and the worst when it followed normal tillage and puddling for rice. Root biomass data suggest that deep tillage resulted in better and deeper rooting. This research area deserves more attention in the future.

Soil physical data from the Pantnagar experiments provide evidence of other benefits of zero tillage. Infiltration rates and hydraulic conductivity were almost 100% higher in conventionally tilled wheat plots at the CRI stage. A consequence of higher infiltration rates is that significantly more water must be applied to effectively irrigate conventionally tilled plots. Farmers experimenting with zero tillage in Haryana, India, and in Pakistan have observed quicker irrigation and water saving without sacrificing yield. Reduced leaching, especially of nitrogen, has a bearing on nutrient conservation. If almost double the water is applied in normally tilled plots, more nitrogen will be moved out of the root profile. It would also be useful to plot infiltration rate over time to determine whether there are differences in steady-state infiltration rates for ZT and NT. Since zero-till plots are not tilled, we expect their soil physical properties to be better and steady-state infiltration to be higher.

In practice, zero tillage saves time between the rice harvest and wheat planting, especially on heavier soils with poor drainage (Hobbs et al 1998), resulting in a better chance of planting wheat at the optimal time. Data from many experiments have shown that wheat yields decline by 0.7–1.5% per day of delay from optimum planting time (Saunders 1990, Hobbs 1985, Randhawa et al 1981, Ortiz- Monasterio et al 1994). In Pakistan, Aslam et al (1993) observed 10–44 d of delay in planting wheat using the farmers' practice over zero tillage, resulting in a mean yield advantage of 41% for zero tillage. This advantage must be incorporated into future experiments that compare normal and zero-tillage methods, otherwise results will not reflect this advantage.

These experiments did not include transplanting into unpuddled soils or direct seeding onto puddled soils. These two further treatments need to be evaluated in the region. In China and some areas of South Asia, especially in poorly drained, heavy soil conditions, transplanting seedlings into soil that has not been plowed or puddled is practiced. Advantages of this system include less damage to soil physical properties and better wheat crops. Water use would need monitoring since this practice may not be feasible where water is limiting. Direct seeding on puddled soils is another alternative. This improves weed control and removes drudgery in transplanting.

In the next 20 years, rice and wheat productivity have to be increased to meet the demands of increasing human population in South Asia. New land will not be available and most agricultural land is already cropped with two or even three crops per year. In addition, increased crop productivity must come with an increase in efficiency of inputs at lower cost and by saving natural resources. Direct seeding of rice and zero-till establishment of wheat are one way to accomplish this in the rice-wheat systems of South Asia. Direct seeding of rice saves energy and water for rice establishment and eliminates drudgery in transplanting. It can result in earlier maturity of rice, which helps improve wheat productivity through timelier establishment. Zero tillage of wheat also enhances the chances of timely planting, has been shown to save water and reduce N-leaching losses, and results in less grassy weeds (Malik et al 1998). Zero tillage drastically reduces the consumption of fossil fuels and the wear and tear of tractor parts and accessories. Zero tillage also allows crop residues to be left on the soil surface after harvest if suitable drills are available. This means that farmers do not have to burn residues to prepare land for the next crop. This plus savings in fuel use would significantly reduce carbon emissions into the atmosphere and the risk of global warming. For these reasons, more emphasis must be given to fine-tuning and accelerating the adoption of this technology in South Asia, including the development and availability of suitable equipment to make this technology a success.

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Notes

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Overcoming constraints in direct-seeded rice

Mechanization issues in tillage and crop establishment for dry direct-seeded rice

R.R. Bakker, M.A. Bell, and J.F. Rickman

As labor is being drawn away from agriculture, rice farmers in Asia increasingly adopt various labor-saving technologies. Traditional methods of tillage and crop establishment are being replaced, and the use of mechanization in farming operations is increasing. This paper addresses how mechanization can help alleviate some of the constraints to achieving higher productivity in dry direct-seeded rice by highlighting examples from recent research. Mechanization can lead to more timely crop establishment, reduce weeding cost, reduce variability in emergence, and lead to better control of water movement in the field. Some common constraints to the successful adoption of mechanization by rice farmers are reviewed as well.

Soil tillage and crop establishment are relatively labor-intensive activities for rice in Asia. As economies in the region develop, labor is being drawn away from rice production, resulting in late-established crops and lost revenue because of delayed harvesting. At the same time, there is a tendency to further intensify rice production through double- and triple-cropping systems. Rice production systems throughout Asia are changing in response and farmers are now moving from manually intensive to various labor-saving technologies. For instance, the rising labor cost and the need to intensify rice production have led to changes in crop establishment method for rice (Pandey and Velasco, this volume). The traditional transplanting method is being replaced by direct sowing on dry-tilled soil (dry seeding) or puddled soil (wet seeding). Changes in crop establishment have important implications for farm operations including primary tillage, seedbed preparation, planting, weeding, and water management.

Coinciding with changes in crop establishment is the growing use of farm machinery in rice production. For instance, tillage operations are increasingly carried out by the use of mechanical power sources such as power tillers and tractors, replacing manual labor and animal draft power for tillage. The development of higher levels of mechanization can be illustrated by a recent review of the status of mechanization throughout Asia (Salokhe 1998). For example, the use of tractors and power tillers in agriculture in Thailand increased by a factor of 6–7 in a 15-y period (1978-93, Fig. 1). Similar trends have occurred in India, Vietnam, Malaysia, Indonesia, and Bangladesh. Although initially tractors were used on large, plantation-type farming systems, current tractor owners rely largely on contract operation to serve many smallholder farmers. Mechanization plays an increasingly important role in smallholder production agriculture in Asia, particularly for rice.

Changes in crop establishment and increasing availability of mechanical power raise two relevant questions: (1) How can mechanization help alleviate some of the constraints associated with direct seeding? and (2) What constrains the successful adoption of mechanization by farmers? This paper concentrates on the potential role of mechanization in dry direct-seeded rice production, although some of the issues raised apply to wet-seeded rice as well. For conciseness, the role of irrigation pumps will not be taken into consideration, despite their increasing significance in rice production systems.

Constraints to achieving higher production in dry-seeded rice and the role of mechanization

Commonly reported constraints to achieving higher productivity in dry-seeded rice involve delays in land preparation leading to late crop establishment, excessive weed infestation, uneven crop emergence, and poor water control. Although farm mechanization is often not directly associated with yield increases, it can lead to more timely crop establishment, reduce weeding costs, reduce variability in emergence, and lead to better control of water movement. In addition, mechanization may result in increased cropping intensity and allow families greater flexibility in seeking off-farm or nonfarm employment (Duff 1986).

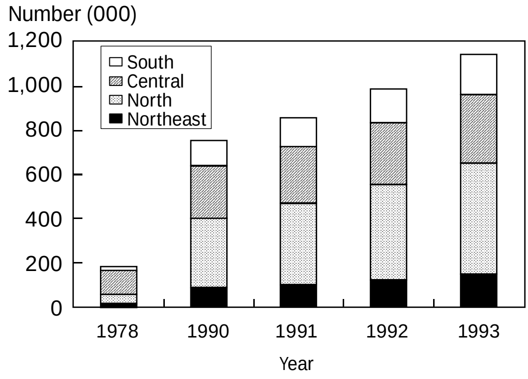

Fig. 1. Number of 2-wheel tractors (5–12 hp) in Thailand, 1978-93. (Adapted from Salokhe 1998.)

Options for mechanized farm operations in dry-seeded rice fall into three broad categories: soil tillage, mechanical row seeding, and reduced-tillage systems (sometimes referred to as conservation tillage). Special operations such as precision leveling and subsoiling can be categorized under soil tillage and are carried out intermittently (i.e., not every cropping season). Mechanical row weeding by tractor-drawn implements as practiced in many farming systems in industrialized countries has not yet received great interest in rice production in Asia. This may be due to various factors such as the low opportunity cost of family labor, lack of access to tractors during weeding time, high cost of mechanical weeding, and others.

Soil tillage

The objective of soil tillage in dry direct-seeded rice is to prepare a suitable seedbed by (1) destroying weeds and incorporating crop residues and manure, (2) improving soil aeration, (3) improving infiltration capacity, and (4) improving seed-soil contact by changing the aggregate distribution (Morris 1982). Tillage operations can also prevent emergence of weeds and improve soil structure in specific situations, such as breaking up impermeable soil layers. Apart from irrigation pumping, soil tillage is often the first farm operation that is mechanized as it requires the highest amount of energy in agriculture (Rijk 1986). The suitability of soils to mechanized tillage can be characterized by the workability (or tillability) and trafficability of a soil. Workability can be defined as the relative ease by which a soil can be manipulated for a specific purpose; it is a measure of how much energy is required for tillage (Hoogmoed 1999). Trafficability is a measure of how well the soil will support the equipment used during tillage to operate the equipment effectively (Krause and Lorenz 1984). The workability and trafficability of a certain soil type are strongly affected by moisture content and soil structure. Dry soils have a higher energy demand for tillage than moist soils, and well-structured soils have a lower energy demand than poorly structured soils. Soils with a lower moisture content exhibit less equipment sinkage and soil compaction (i.e., better trafficability), whereas soils with a higher moisture content exhibit a higher tendency to compact under equipment loads, possibly causing adverse conditions for crop growth. Generally, a shift to higher levels of mechanization will also lead to a shift in workability range, as operations can start earlier in the monsoon season. In practice, farmers or farm contractors often depend on trial and error when deciding on the best time to start tillage operations.

The most commonly cited advantage of mechanizing tillage in dry direct-seeded rice is the increased mechanical power that is available to cultivate the soil. With higher levels of mechanization, tillage can be started at lower soil moisture content, and less time is needed to complete tillage operations, which may lead to a more timely crop establishment. Besides timeliness, a shift to higher levels of mechanization is often accompanied by a shift from traditional implements (e.g., animal plow, moldboard plow, spike tooth harrow) to more modern tillage implements (disc plow, disc harrow, cultivator, rotovator, etc.) as indicated in Table 1. Using modern implements for tillage leads to more uniform seedbed preparation, reduces field variability, and increases the energy efficiency of the operation. Therefore, mechanization can

Table 1. Tillage implements used in dry-seeded rice.

Mechanical power source	Main implements for primary tillage	Main implements for secondary tillage	Other implements
Hand labor	Hand hoe	Hand hoe	Rake
Animal draft plow, moldboard plow	Traditional wooden roller harrow	Spike tooth harrow,	Ridgers, weeders
Two-wheel tractor	(Moldboard plow)[a]	Spike tooth harrow	Ridger
Small 4-wheel tractor (<20 kW)	Disk plow, rotary tiller	Disk harrow, rotary tiller	Mechanical weeder, leveling board
Larger 4-wheel tractor (>20 kW)	(Moldboard plow), disk plow, disk tiller, chisel plow, rotary tiller	Disk harrow, field cultivator, spring tine harrow, roller, packers	Subsoiler, bucket scraper, leveling board, mechanical weeders

[a]In parentheses = less common.

lead to better crop emergence and crop yield, although the relationship between tillage activities and crop yield is complex.

In view of the significant weed infestation problems often encountered in dry-seeded rice, weed control is frequently viewed as the primary objective of tillage (Morris 1982, Moody 1982). Timeliness of tillage can play a direct role in weed control, as in postharvest tillage (i.e., instead of leaving the field fallow in the dry season, the field is plowed after harvesting the previous crop) or in the use of the stale seedbed technique (after primary tillage, weeds emerge and are subsequently destroyed prior to seeding). In both cases, mechanization allows farmers greater flexibility in planning tillage operations. Mechanized tillage systems may also reduce the variability of field levels, leading to better water control during the later stages of plant growth, and result in reduced labor for hand weeding. With increasing levels of mechanization, land leveling (combined with secondary tillage or as a separate operation) will become more important in rice production systems, especially those relying on the dry-seeding method. The objective of land leveling is to bring about uniformity in water depth across the field to facilitate good drainage, fertilizer-use efficiency, and crop yield. The following case studies illustrate the impact of mechanization of tillage operations on the productivity of dry direct-seeded rice.

My et al (1995) describe the mechanized tillage pattern for dry direct-seeded rice in Long An Province (Mekong Delta) in Vietnam, where both primary and secondary tillage operations are carried out by four-wheel tractors (50–80 hp) equipped with rotovators. The most common tillage pattern is primary rotavation prior to rainfall to loosen the soil, followed by a 4-wk period to germinate weeds, and subsequent seedbed preparation by rotovator and seeding on the same day. The main reason for adopting dry-seeded rice in this area is to enable a double-cropping system. Mechanizing tillage is considered crucial for early establishment of the first crop and to reduce labor bottlenecks during the entire crop establishment period. The success of the system in Long An is attributed to good arrangements between farmers and contractors for scheduling of tillage operations (i.e., demand for equipment is spread out over a longer period). Early completion of tillage operations also avoids problems of trafficability later in the season, when heavier soils become too sticky for normal equipment operation.

Yadav (1995) describes tillage systems for dry-seeded rice (DSR) on farms in Pangasinan, Philippines, where farmers have adopted DSR because of significant reductions in labor for crop establishment compared with transplanting. Tillage operations are largely based on using animal draft power with the conventional moldboard plow and contracted 75-hp tractors with disc harrows, and often combinations of animals and tractors are used. In all cases, a final harrowing operation is carried out to cover broadcast seeds. The author recommends that the use of the tractor for primary tillage be promoted to reduce farmers' dependence on rainfall occurrence and allow for more rainwater conservation. Saleh and Bhuiyan (1993) consider the unavailability of tractors during peak periods in the area to be a major impediment to the further adoption of DSR. They stress that earlier tillage by tractors would result in more effective weed control by exposing tilled soil for several days before final seedbed preparation.

Rickman et al (1997) report on the growing number of four-wheel tractors in the northern provinces of Cambodia, where approximately 70% of the rainfed lowland rice area is established by broadcasting dry seed. In general, tillage operations start with plowing with three-point linkage disc plows, followed by a second plowing. Seed is then either broadcast and harrowed into the soil or left on the surface. Although several hand-held walking tractors have been imported into the country, farmers prefer four-wheel tractors because they reduce drudgery to a larger extent. The majority of farmers use an additional plowing operation at approximately 40–60 d after seeding to control weeds and improve plant tillering. A similar system of tillage after seeding and crop emergence is used in the Indian *beushening* system (Tomar, this volume).

Lantican et al (1999) studied the relationship between land-leveling precision and grain yield in the same study area in the Philippines and concluded that yield for DSR was significantly correlated with precision of land leveling. Mean standard deviation for land-leveling precision was 8 cm and farmers lost 925 kg ha^{-1} of yield because of land-level deficiencies. Fields with higher leveling precision showed a significantly lower seasonal water stress, as represented by the water deficit index. Rickman et al (1999) compared crop yields of transplanted and dry-seeded rice on 14 farms in Battamba, Cambodia, and concluded that leveling increased crop yields significantly for both transplanted and dry-seeded fields (Fig. 2).

Mechanical row seeding

The most widespread method for establishing dry direct-seeded rice is broadcasting seed by hand on tilled soil. In areas where the use of chemical weed control is limited, farmers have developed and adopted alternative methods for broadcasting (e.g., hand dibbling, furrow seeding) to enable faster hand weeding between rows. These methods are typically labor-intensive and provide a potential labor bottleneck in establish-

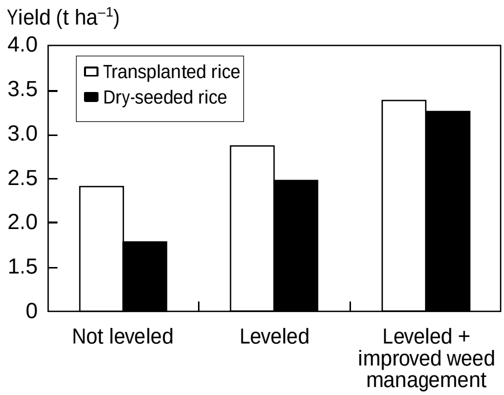

Fig. 2. Effect of leveling on crop yield of transplanted and dry-seeded rice in 14 farmers' fields, Battambang Province, Cambodia. (Adapted from Rickman et al 1999.)

Table 2. Features of broadcasting and row-seeding methods for dry-seeded rice.

Method	Field capacity (h ha^{-1})	Labor requirement (persons)	Advantages	Disadvantages
Broadcasting	4	1	Speedy operation Requires seed covering Shallow seed placement Susceptible to rats, birds	High seeding rate
Hand dibbling	40	4–5	Facilitates in-row weeding Low seeding rate	Labor-intensive
Furrow seeding	30	3–4[a]	Facilitates in-row weeding Requires use of animal Requires additional labor for furrow closing	Labor-intensive
Hand operated (push-type) seeders	15	1	Facilitates in-row weeding No fuel costs range	No closing of furrow Shallow seed placement Limited workability
Animal-drawn or tractor-mounted mechanical row seeders	4–12[b]	1	Reduces drudgery Facilitates in-row weeding Deeper seed placement Automatic seed covering Adjustable seed rate + depth Combination with reduced or minimum tillage possible	Requires use of tractor Limited workability range Seed clogging Requires access to fields

[a]1 person for plowing, 1 or 2 for sowing, 1 for closing furrows. [b]Depending on number of rows, machine speed.

ing the crop in a timely manner. Table 2 presents some general features of broadcasting and four row-seeding methods for dry direct seeding of rice, including options for mechanical row seeding. Mechanical row seeding (i.e., using some type of mechanical implement to place the seed under the soil surface) can considerably reduce labor requirements of establishing dry-seeded rice and further improve emergence by placing seeds at a more uniform depth in the seedbed. In unfavorable rainfed environments, mechanical seeding may be important in reducing drought stress of seedlings by providing better seed covering after seeding.

When considering a mechanical seeding method, seedbed preparation requirements should be evaluated along with the seeding method. Although certain seeders require a fine, leveled seedbed that is free of weeds, others can be used in more variable circumstances including reduced-tillage systems (e.g., IRRI's vertical-metering slit seeder) or require no previous tillage operation at all (e.g., tractor-mounted seed drills). An intermediate form of broadcasting and row seeding is the system followed in California, where fields are ridged at approximately 15-cm spacing and then flooded before rice is air-seeded. The seed falls through the water and accumulates at the bottom of small furrows, resulting in a crop that appears as if it has been sown in rows. A somewhat similar system was evaluated at IRRI, where, after ridging, seed was broadcast on dry soil with subsequent harrowing and flooding of the field (Bell et al 1999). There are several technical concepts of mechanical row seeders—for hand operations (push-type), animal draft power, and two-wheel and four-wheel tractors. Although many row seeders have been tested and evaluated at research stations, few have been commercialized successfully.

Often-reported constraints of mechanical seeders are limited seed flow (rice seed does not flow as well as most other grains, creating frequent seed bridging and clogging problems), limited residue-handling capability (few commercial models have trash cutters), and limited workability range (in particular on heavier textured soils: if too wet, soils will stick to the seeder parts and prevent proper operation). In addition, field layout is often a constraint for tractor-mounted seeders, as crossing bunds and neighboring fields with a large machine can be a major limitation on smallholder farms. Farm-level investigations provide further evidence of advantages and constraints of mechanical row seeding.

Moreau et al (1988) evaluated the adoption potential of a hand tractor-mounted two-row seeder by farmers in Thailand compared with conventional broadcasting. The hypothesis was that prospects for the adoption of mechanical seeding technology were high as row seeding would lead to a more uniform plant stand and faster and more efficient weeding between rows. Results in farmers' fields confirmed that mechanical row seeding led to better emergence; however, increases in crop emergence remained futile if further field variability-enhancing factors (particularly control of water movement during the growth season) could not be controlled. Second, row seeders were only technically feasible in field plots that were easily reachable with two-wheel tractors, and machine use was only economically profitable in fields with high weed infestation (because of a higher reduction in weeding costs). A study of socioeconomic characteristics of farmers' families in the area suggested that only families with significant incentives to increase labor productivity (i.e., families that can easily find alternative employment) would benefit from investment in the new technology.

Manaligod et al (1996) compared the IRRI vertical-metering slit seeder with hand broadcasting in a rainfed rice system in the Philippines and concluded that, when drought stress occurred after seeding (i.e., very little rainfall 2 wk after seeding), mechanical seeding was superior to broadcasting. However, in seasons with sufficient rainfall, differences in crop emergence and yield were not significant. In this case, adoption of mechanical seeding by farmers would depend on the perception of risk associated with dry seeding, as higher costs for improved seeding technology would be largely seen as an “insurance payment” against low yields rather than as an investment to achieve higher yields.

Rickman et al (1999) reported that crop lodging is a significant problem in dry-seeded rice in Cambodia, particularly with traditional varieties. Lodging was reduced by partially incorporating the seed by harrows or by using a seed drill. A study in 1998 showed that machine drilling seed reduced lodging to less than 10%. When the seed was partially incorporated using drag harrows after broadcasting, 15% of the total crop lodged. In the same trial, 45% of the nonincorporated dry-seeded crop lodged.

Reduced- and zero-tillage systems

The wider availability of herbicides and further development of farm machinery have made it possible to reduce or omit soil tillage operations prior to seeding, particularly where the primary objective of tillage is weed control. Generally, a distinction is made between systems where tillage and seeding are combined into one operation (reduced or minimum tillage) and systems where seed is placed in the soil without any tillage (zero tillage). The major feature of these systems is that the crop can be established with the least amount of soil disturbance: this is in sharp contrast with turning topsoil completely, as in the case of tillage by moldboard plow. In many industrialized countries, entire mechanized systems for reduced or zero tillage have been developed that rely on four-wheel tractors and specialized seed-drilling equipment, in conjunction with chemical weed control. Their success can be attributed to (1) reduced soil erosion, (2) improved soil water management, and (3) reduced production costs (i.e., reduced number of operations in the field).

A wide variety of equipment has been developed for reduced and zero tillage of cereals, including seeders with discs (e.g., the common triple-disc seed drill: fluted coulter that cuts through plant residue followed by a pair of plain discs that make a V-shaped furrow), tined furrow openers, tined openers combined with shallow rotovators, and strip-till systems (i.e., only a narrow strip is tilled in which the seed is planted). In general, systems with discs are better capable of handling residues in the field and seeding in harder soils, whereas tined openers are cheaper but susceptible to clogging with soil or residue. In India, four-wheel tractor-mounted seed drills have been developed that combine seeding with deep fertilizer placement (e.g., seed-cum-fertilizer drills; Verma 1986). The reduced-tillage machinery in India is extensively used for establishing cereals other than rice, such as wheat. However, experiences with rice are generally limited.

Chinese engineers have developed a seeder for use with a 12-hp, two-wheel diesel tractor that provides tillage and seeding in one operation (Hobbs et al 1997). This system consists of a shallow rotovator followed by a six-row seeding system and a roller for soil compaction. Through the Rice-Wheat Consortium, several systems were imported from China into the Indo-Gangetic Plains of Nepal, India, and Bangladesh. On-farm research has shown that net returns surpass returns to the farmers' current practice because costs for tillage are lower. Bell et al (1999) evaluated several commercial seeder systems for reduced- and zero-tillage seeding of rice, including the Chinese seeder, and reported that field rutting and rice seed flow were problems for the tractor-mounted seeders. Residue management was difficult for the zero-till systems, as none of the seeders had trash cutters. Finally, many of the seeders required a well-leveled surface to work properly.

Although there is great interest in applying reduced- or zero-tillage systems for seeding rice, adoption so far has been limited. Mechanization aspects that may contribute to limited adoption are the need for heavier tractors and more complicated seeding technology, making it suitable only in areas with higher levels of mechanization (e.g., northwestern India, Pakistan, parts of China). In addition, contract hiring may significantly reduce the flexibility of farmers in choosing a seeding date, as they depend on the availability of the contractor. Finally, given the significant weed problems often encountered in dry-seeded rice, reduced or zero tillage may further aggravate weed infestation. Sarkar and Moody (1983) mentioned that application of zero tillage in rice has led to many different results with regard to weeds. Often, perennial weeds become a problem over time, which cannot be effectively managed without tillage.

Constraints to adopting mechanization

The single most important constraint to adopting mechanization at the farm level is the higher cost associated with the use of machinery on small farms. Even if machinery is sufficiently scaled down to fit the small farming system, capital and operating costs per unit of machine are higher than in farming systems in industrialized countries (Chancellor 1986). When considering mechanization, therefore, options to lower cost should always be pursued. These include reducing the production costs of machinery (e.g., by localizing manufacturing), using secondhand or reconditioned machinery, designing machinery for multiple purposes, or spreading out machinery costs over a bigger area. In many cases where mechanization is used successfully, a combination of these cost-reducing factors has contributed to the success. For example, Chinese-made power tillers that consist of a two-wheel tractor with a rotovator are now the main power source for tillage in Bangladesh. The success of two-wheel tractors can be attributed to their low acquisition cost, multipurpose capability (wet tillage, dry tillage, water pumping, transportation), and contractor ownership that makes the technology widely available to small farmers.

Another constraint to the adoption of mechanization is the ability of local communities to provide maintenance and service related to the use of farm machinery. In Bangladesh, the introduction of power tillers has led to a flourishing of small repair and maintenance shops, in addition to the manufacturing of spare parts by local manufacturers. The availability of services and spare parts to users is crucial for the sustainable use of imported machinery. Furthermore, with higher levels of mechanization, more knowledge-intensive technology is introduced, which prompts the need for better education and training of those involved in operation and maintenance. Often, mechanization has been introduced without proper implementation of a training program, leading to dissatisfaction of farmers and, ultimately, rejection of the technology.

Finally, factors that prevent development and adoption of mechanization can be found at the regional or national level: inappropriate government support for the introduction of machinery (top-down approach), absence of standardization of machinery, or importation policies that discourage local manufacturing. A strategy for successful mechanization of farm production in developing countries was presented by Clarke (2000). Rather than making policies that will stipulate by which means or how much agriculture will be mechanized, governments should strive to establish conditions that will ensure free and undistorted development of appropriate mechanization. This development will largely be based on good linkages among farmers, retailers, manufacturers, and importers, where the government has a largely subsidiary role of facilitating these linkages and providing education and extension.

Summary and research needs

Mechanization can play an important role in alleviating constraints in dry direct seeding. In areas where timely establishment of direct-seeded rice is important, mechanization of tillage is often crucial in preparing an adequate seedbed in time. Furthemore, mechanization of tillage often leads to the adoption of nontraditional tillage implements (e.g., replacement of animal plow with disk plow or rotovator). Mechanical row seeding offers labor-saving benefits in areas where farmers have adopted traditional row seeding, and can result in improved drought tolerance and emergence and reduced lodging. Workability of the soil, however, is a limiting factor in the suitability of mechanical seeders in rainfed systems. Zero- or reduced-tillage systems for rice may reduce production costs by combining tillage and seeding operations, but require more sophisticated machinery that can handle field residues effectively.

To further assess the benefits and costs of mechanization in direct-seeded rice, a more in-depth study of production systems in which mechanization has been successfully adopted would be useful. Besides costs for operation and maintenance of machinery, such studies should address to what extent the availability of mechanization has reduced farmers' perception of risk, in addition to other nonmonetary factors such as drudgery. Furthermore, benefits of mechanization should be addressed from a systems perspective rather than in isolation, as adoption of mechanization has often taken place along with improvements in seed quality, water management, weed control, and fertilizer use. Finally, we suggest that the development of new technology focus on providing cost-effective methods for land leveling, as reducing the unevenness in a direct-seeded field can improve yields and increase water- and fertilizer-use efficiency.

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On-farm seed priming to improve crop establishment and yield in dry direct-seeded rice

D. Harris, R.S. Tripathi, and A. Joshi

Seed priming differs from pregermination in direct-seeded rice. Primed seed—seeds soaked overnight in water and then surface-dried and immediately sown—will only germinate in moist soil. Pregerminated seed, on the other hand, has a protruding plumule and radicle, typically broadcast onto puddled soil, and is susceptible to damage during sowing. It will continue to germinate, even when sown under inappropriate soil conditions. Moreover, if broadcast on a free water surface, primed seeds sink quickly, whereas pregerminated seeds float and risk being redistributed by the wind, resulting in patchy stands.

Work with farmers on upland rice in South Asia has demonstrated that priming seed with water before direct sowing has many advantages. Primed seed germinates and emerges faster (1–3 d) and more uniformly and seedlings grow more vigorously, leading to a wide range of phenological and yield-related benefits. Glasshouse experiments showed that a delay in emergence of rows of rice by 1 to 3 d reduced seedling vigor by 20% to 45%. In addition, primed crops often flower and mature earlier and give higher yields. In 2 years of on-station experiments in Rajasthan, India, priming seed of 10 upland rice cultivars resulted in statistically significant mean yield increases in 1997 (1.7 t ha^{-1} vs 2.0 t ha^{-1}, or an increase of 18%) and in 1999 (0.6 t ha^{-1} vs 0.84 t ha^{-1}, an increase of 40%). In 1997, priming resulted in better emergence (91% vs 61%), earlier flowering (71 d vs 74.7 d), taller plants (108 cm vs 94 cm), longer panicles (22.4 cm vs 20.3 cm), and more panicles $plant^{-1}$ (5.7 vs 4.9).

Very early capture of resources appears to be important in determining some of the benefits associated with seed priming and a hypothesis to explain this response in upland rice is discussed. Recently published data on resource partitioning in young rice seedlings showed that the superior early growth vigor of *Oryza glaberrima* in relation to *O. sativa* was due to the early onset of autotrophic growth, a high degree of resource partitioning to leaves, and a large specific leaf area. These data are reinterpreted here to show that faster emergence following seed priming could result in better resource capture that might contribute to growth and yield advantages associated with priming.

Evidence is accumulating from recent research in a range of crop species and countries showing that fast germination, early emergence, and vigorous seedling growth may result in higher yielding crops (Harris 1996, Harris et al 1999, 2000, Musa et al 1999). A simple, low-cost, low-risk method of promoting rapid seedling establishment and vigorous early growth is by on-farm seed priming, in which seeds are soaked in water for some time before surface drying and sowing. The duration of soaking is critical and should always be less than the safe limit for each crop cultivar. The safe limit is defined as the maximum length of time for which farmers should prime seeds and which, if exceeded, could lead to seed or seedling damage by premature germination (Harris et al 1999). This concept of the safe limit differentiates on-farm seed priming from pregermination. Primed seeds will not continue to germinate unless placed in a moist soil environment, where they quickly imbibe a further small amount of water and germinate rapidly. However, if primed seeds are sown into a seedbed that has inadequate moisture, they will not germinate unless moisture subsequently becomes available, for example, if it rains. In contrast, seeds that have been soaked for longer than the safe limit will continue to germinate even in the absence of an external moisture source. Using pregerminated seed presents inherent risks, whereas primed seed behaves as dry seed if sowing is delayed or seedbed conditions are suboptimal.

Safe limits for a range of major crops are compatible with soaking in water overnight. Harris et al (1999) and Musa et al (1999) used priming for 8 h to produce large yield benefits in chickpea. Harris et al (1999) noted that priming maize for 24 h was safe, although farmers in India and Zimbabwe modified this to overnight for practical reasons (Chivasa et al 1998). Soaking overnight was also successful for sorghum (Harris 1996, Harris et al 2000, A. Rashid, personal communication), wheat (Harris et al 1999, A. Rashid, personal communication), mungbean, and pearl millet (A. Rashid, personal communication).

Harris and Jones (1997) showed that priming for 24 h effectively speeded up germination among a range of diverse upland rice cultivars. This and other in vitro work led to the recommendation for farmers in India to soak rice seeds for 24 h before sowing paired-plot trials in 1996 (one plot with primed seed, one adjacent plot sown using the same amount of nonprimed seed). Farmers generally used only dry seed but they were encouraged to adapt the priming method according to their own needs. They immediately decided to soak seed overnight rather than for 24 h because it was more practical (Harris et al 1999).

Indian farmers' perceptions of priming rice in 1996 were very favorable. They reported that primed crops emerged faster, grew more vigorously, flowered and matured earlier, and produced higher yields than nonprimed crops (Harris et al 1999). In addition, some farmers reported that weeding was less onerous, perhaps because early, vigorous growth allowed rice to compete more favorably with weeds.

In this paper, we present data from additional farmer participatory trials of priming rice in India in 1998, together with the results of on-station experiments in 1997 and 1999. We also present data from glasshouse experiments designed to explore the relationship between time of emergence of rice seedlings and competition with weeds, using rice as the "weed." Finally, we discuss a hypothesis that may explain priming-induced seedling vigor as a consequence of better early capture of resources.

Materials and methods

Farmer participatory trials

In kharif (rainy season) 1998, seven farmers in Bar village, Gujarat, India, were each given 2 kg of seed of rice cv. Kalinga III and asked to soak half the seeds overnight, surface-dry them, and then sow them in a plot adjacent to a plot sown with nonprimed seeds. Farmers' own cultural practices were observed in both plots. Farmers harvested each plot separately, while researchers measured grain yield and area of each plot.

Several methods, based on CARE (1989), were used to facilitate the evaluation of trials by farmers and to elicit constructive feedback. Farm walks were conducted twice during each season to promote discussions among farmers about the advantages and disadvantages of the technique. These walks allowed individual farmers to assess the technology at different stages of crop development and over a wide range of sowing dates, soil types, varieties, and levels of management represented in that village. Farm walks were usually followed by semistructured focus group discussions (FGDs) in which farmers were asked to decide on the merits of seed priming relative to their normal practice in several mutually agreed categories relating to agronomy, crop development, and yield.

On-station trials

On 5 July 1997, 10 upland rice varieties (PNR-381, RRU-104, Vagad Dhan, RRU-5, Dangar, RRU-665, RRU-664, Patharia, RRU-102, and Kalinga III) were sown using farmers' practices (plowing using bullocks and a wooden plow, sowing by hand followed by planking, no added fertilizer) at the field station of the Rajasthan Agricultural University in Banswara, India. The experimental design was a randomized split plot in three replicates, with priming as the main plot and variety as the subplot. The subplot size was 5 × 2 m. There were three priming treatments—nonprimed seed, seed primed overnight in water, and seed primed overnight in 2% NaCl solution. The latter treatment was included because rice farmers in Rajasthan use salt water to remove nonviable seeds before sowing. We wanted to check whether extended exposure (overnight) of seed to the salt solution was risky. The trial was repeated on 2 July 1999, with seeds of PNR-381 and RRU-664 replaced by RRU-9 and RRU-28. Grain yield was measured in both years. Components of yield were measured only in 1997.

Glasshouse experiments on competitiveness and vigor

An experiment was designed to simulate the advantage gained by rice plants in competitive situations following priming. It is argued that the most effective competition for rice plants is other rice plants since they occupy a similar ecological niche. Consequently, seeds of Kalinga III rice were sown in soil at field capacity in large trays (0.5 × 0.35 × 0.18 m) (Fig. 1). Ten seeds per row were sown and seedlings were thinned on emergence to leave five regularly spaced plants at positions A and B. "A" plants were designated as the "crop" and sown on day 0, while "B" plants were designated as "weeds" and were sown on days 0, 1, 2, or 3 according to treatment to simulate delayed emergence of nonprimed weed seed relative to primed crop seed. A further treatment contained only four A rows and represented the "no competition from weeds" situation, in which only within-crop competition would be expressed. All seeds were actually primed to promote rapid emergence and minimize the effect of possibly declining water potential in the seedbed. No further water was added and shoot fresh weight was measured for A rows and B rows separately, 25 d after sowing. Separate comparisons were made on the performance of A rows between treatments and the performance of B rows between treatments, following analysis of variance. There were six replicates and the experiment was run twice, in heated glasshouses at the University of Wales, Bangor, UK, in April and June 1998.

Results

Farmer participatory trials

In Bar, farmers' perceptions were similar to those of 56 farmers in four other villages in this part of western India reported by Harris et al (1999)—faster emergence, improved seedling vigor, early flowering, shorter duration, and higher yields—although the authors were unable to measure yields directly. Even in situations where sowing was done onto standing water, farmers reported that primed seeds sank promptly, whereas dry seeds floated and were often blown by the wind, resulting in a clumped distribu-

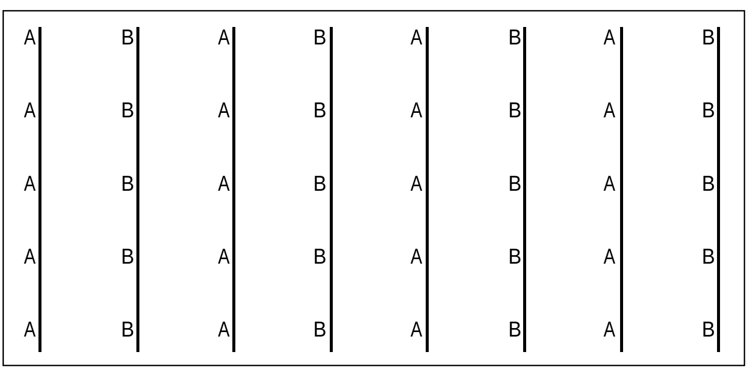

Fig. 1. Planting design for competition experiments using Kalinga III rice. A = crop, B = weed. B rows were sown 0, 1, 2, or 3 d after the A rows.

tion (Harris et al 2000). This finding closely agrees with that of Saikia et al (1989), who reported significant yield advantages in sowing primed seed on flooded fields in Assam relative to dry seed and pregerminated seed. In the current study, clear yield benefits from priming were obtained in all seven trials measured (Fig. 2), with a mean yield increase of 23%.

On-station trials

Yield data for 2 years are summarized in Table 1. Averaged over 10 varieties, grain yield from primed crops was higher than that of unprimed crops by 18% in 1997 and 40% in 1999, a drier year in which no rain at all fell during August. In 1997, ancillary measurements were made (Table 2). Compared with nonprimed seed, priming seeds overnight in water resulted in better emergence (91% vs 61%), earlier flowering (71 d vs 74.7 d), taller plants (108 cm vs 94 cm), longer panicles (22.4 cm vs 20.3 cm), and more panicles plant^{-1} (5.7 vs 4.9). Priming with 2% NaCl solution had most values intermediate between those of primed and nonprimed treatments.

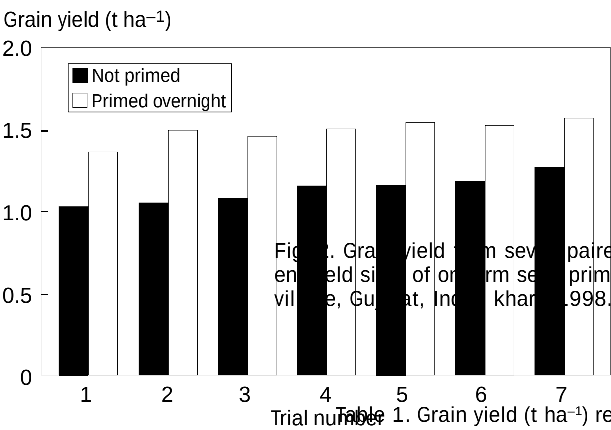

Fig. 2. Grain yield from seven paired-plot trials at seven different field sites of on-farm seed priming of Kalinga III rice in Bar village, Gujarat, India, kharif 1998.

Table 1. Grain yield (t ha^{-1}) response of rainfed rice to seed priming at Rajasthan Agricultural University, Banswara, India, kharif 1997 and 1999. Values are means of 10 cultivars.

Treatment	1997	1999
Dry seed	1.7	0.6
Primed overnight (water)	2.0	0.8
Primed overnight (2% NaCl)	2.0	0.8
LSD at 5%	0.17	0.12

Table 2. Components of yield for the response of rainfed rice to seed priming at Rajasthan Agricultural University, Banswara, India, kharif 1997. Values are means of 10 cultivars.

Variable	Dry seed	Primed (water)	Primed (2% NaCl)
Emergence (% at 3 DAS)[a]	12.6	72.0	63.5
Emergence (% at 18 DAS)	60.7	90.8	72.7
Time to 50% flowering (DAS)	74.7	71.0	72.1
Plant height (cm)	94.1	108.0	91.9
Panicle length (cm)	20.3	22.4	18.5
Panicles plant^{-1}	4.9	5.7	5.2
Grain yield (t ha^{-1})	1.7	2.0	2.0
Yield increase (% dry seed)	–	18	13

[a]DAS = days after sowing.

Glasshouse experiments on competitiveness and vigor

The maximum potential productivity for A rows in this experimental system, as measured by the "no competition from weeds" treatment of the June experiment (no. 2 in Fig. 3), was considerably higher than that of the April experiment (no. 1 in Fig. 3), probably because of the higher temperatures encountered (which were not measured). The fresh weight of the A rows in the "0 delay" treatment was significantly lower than that of those in the "no competition" treatment in both experiments and indicates that the presence of the B rows influenced crop growth as expected.

The response of the A rows relative to the competing B rows was broadly similar in both experiments (Fig. 3). In experiment 1, the shoot fresh weight of the A rows (primed crop) increased in proportion to the delay in the onset of competition from the B rows (nonprimed weed), whose fresh weight remained the same across treatments. The difference between the performance of the A rows under the 0 and 1 d delay and the 0 and 2 d delay was not statistically significant in experiment 1, although that between 0 and 3 d was significant ($P<0.05$). In contrast, in experiment 2, although the fresh weight of the A rows tended to increase (insignificantly with increasing delay), that of the B rows actually declined (although the difference was only significant between 0 and 3 d delay), perhaps because of the faster, temperature-induced growth of the A rows.

Discussion

Results from on-farm participatory trials in India in 1996 (Harris et al 1999) were confirmed by additional farmers' trials in 1998 (Fig. 1). Farmers in this area of India sow rice only after monsoon rains have begun. They do not practice dry seeding before the rains. In this latter situation, priming is unlikely to be of any benefit. Experiments with sorghum seed sown before the rains showed that primed seed simply dries out and behaves identically to nonprimed seed once the rains arrive (data not shown).

Farmers' assertions that priming induced faster, better emergence and early growth, earlier flowering and maturity, and higher yields (Harris et al 1999) were confirmed by the on-station research (Tables 1 and 2). In 1997, higher yields from primed crops were

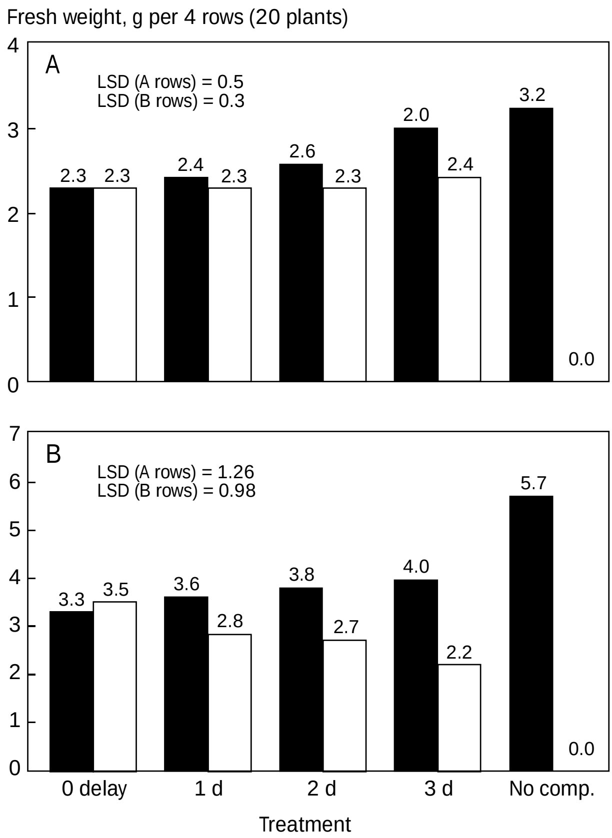

Fig. 3. Shoot fresh weight 25 d after sowing of four rows (20 plants) of Kalinga III rice seedlings sown on day 0 (dark shading; A rows, Fig. 2) and days 0, 1, 2, or 3 (light shading; B rows, Fig. 2). The no-competition-from-weeds treatment represents four A rows grown alone. (A) Rice experiment 1, sown April 1998; (B), rice experiment 2, sown June 1998.

associated with more plants per unit area but also with superior performance per plant (Table 2). This combined response to priming—more complete emergence plus more productive individuals—has also been reported in chickpea (Musa et al 1999) and observed in other crops.

Farmers have noted that primed crops exhibit great early vigor and in some circumstances compete aggressively with weeds (Harris et al 1999). Primed crops commonly emerge 1–3 d earlier following seed priming. Various experiments are in progress to test this hypothesis in maize and rice. The in vitro studies reported here (Fig. 3) suggest that early (by a margin of time similar to that reported in the field, see also Table 2) emergence and the resulting rapid early growth might confer some competitive advantage over weeds that emerge at the normal time.

Recent work by Asch et al (1999), which sought to explain the superior early growth vigor of *Oryza glaberrima* in relation to *O. sativa,* also sheds some light on how faster emergence induced by seed priming may result in greater early vigor. These authors used daily measurements of resource partitioning in young rice seedlings (up to 18 d old) to conclude that *O. glaberrima* was more vigorous than *O. sativa* because of the earlier onset of autotrophic growth in the former.

Data from Asch et al (1999) clearly show differences between the two species in the leaf blade/plant dry weight ratio of approximately 0.14 units (> 50% increase of CG 14 over the less vigorous WAB 56-104) (Fig. 4). The authors conclude that this greater degree of resource partitioning to leaves and a large specific leaf area explain why *O. glaberrima* is so much more vigorous and competitive in weedy situations than *O. sativa*.

Asch et al (1999) used primed seeds for this experiment. Researchers have long been aware that seed priming has advantages in the laboratory because vigorous, synchronous germination is obtained, which allows selection of seedling populations with minimal variability. In Figure 4, we took the original data (primed, broken lines) and simply displaced the curves by 2 d to the right to simulate the performance of nonprimed seed (continuous lines) that emerges 2 d later—a situation commonly reported in farmers' field trials. The vertical lines in Figure 4 represent relative gains in the ratio of leaf blade to plant dry weight because of vigor and variety. Gains from seed priming are marked (0.07 units and 0.1 units for CG 14 and WAB 56-104, respectively). In both

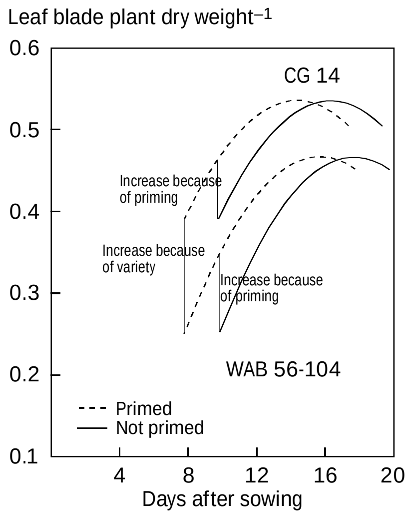

Fig. 4. Ratio of leaf blade dry weight to total plant dry weight for seedlings of rice cv. CG 14 (*Oryza glaberrima*) and cv. WAB 56-104 (*O. sativa*). Broken lines taken from Asch et al (1999); continuous lines displaced by 2 d to simulate the nonprimed situation.

species, they are smaller than the difference between species (0.14 units) under the same sowing regime.

This reinterpretation suggests that faster emergence following simulated seed priming could result in earlier enhanced resource capture than is possible for later-emerging nonprimed seeds. However, very early capture of resources should only be an advantage where the resources in question are subject to competition, such as from weeds, or are ephemeral, such as in seedbeds where moisture, temperature, and other factors can rapidly become limiting.

Conclusions

In vitro, on-station, and farmers' field evaluation trials have shown that, under direct seeding of rice after soil wetting, priming seeds with water before sowing can be beneficial. Thus, upland rice responds to priming in a fashion similar to that of other major crops (e.g., Harris et al 1998, 1999, Musa et al 1999). It is important to reiterate here the difference between priming and pregermination of seeds. Primed seeds will not germinate until they have taken up additional water from a moist seedbed, whereas pregerminated (sprouted, chitted) seeds will continue to germinate regardless of external moisture conditions. Use of pregerminated seed for direct seeding should be avoided. Unlike in nursery beds, seedbed conditions in the open field are generally beyond the control of the farmer, who risks losing the entire seed lot. In contrast, primed seed is not at risk.

The low-cost, low-risk nature of seed priming means that farmers can use it as an insurance policy. If rainfed conditions turn out to be ideal, nothing is lost as primed seed performs as well as nonprimed seed. If, however, the season develops badly and seedbed conditions deteriorate rapidly, small differences in seedling vigor early on can be important (e.g., Fig. 4) and priming will pay off. Farmers should be encouraged to test seed priming in situations in which direct seeding after the onset of rains will be attempted.

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Notes

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Enhancing the performance of dry-seeded rice: effects of seed priming, seeding rate, and time of seeding

L.V. Du and T.P. Tuong

Poor crop establishment and high weed infestation are among the main constraints to the adoption of dry-seeded rice. Field experiments were conducted in the 1998 and 1999 rainy seasons in Binh Chanh, Vietnam, to test the hypothesis that seed priming, seeding rate, and appropriate timing of seeding can improve crop establishment and enhance weed suppression in dry-seeded rice. The experiments were carried out with rice cultivar OMCS94 in a split-plot design, with seeding dates in the main plots, seeding rates (in 1999) or timing of weed control (in 1998) in subplots, and seed priming treatments in sub-subplots. When rice is seeded in very dry soil (near wilting point), priming, especially with 14% KCl solution and saturated $CaHPO_4$ solution, increased established plant density, final tiller number, and grain yields compared with the unprimed treatments. When soil moisture content at seeding was at or near saturation, seed priming decreased established plant density and slightly reduced grain yields compared with the unprimed treatment. Late seeding reduced weed infestation because secondary tillage eliminated weeds that emerged after primary tillage. Using a higher seeding rate to get an adequate stand reduced weed dry weight and increased rice yield, but offered little benefit when the established plant density was already high. Findings suggest that in drought-prone areas, seed priming can reduce the need for using a high seeding rate, but priming can be detrimental if seeding takes place when soil is at or near saturation.

Dry seeding of rice provides an option to increase productivity in rainfed lowland rice ecosystems. Wider adoption of dry-seeded rice, however, is constrained by many problems, the major ones being poor stand establishment and high weed infestation (My et al 1995, Saleh and Bhuiyan 1995).

Poor stand establishment of dry-seeded rice can be attributed to erratic rainfall and frequent droughts after seeding. Harris et al (1999) argued that the speed of germination and emergence is an important determinant of successful establishment in drought-prone situations. Rapidly germinating seedlings could emerge and produce deep root systems before the upper soil layers dry out.

Seed priming is an effective technique for rapid, uniform seed germination of various crops (Lee et al 1998). Primed seeds are those that undergo controlled hydration-dehydration pretreatment before sowing. During hydration, seeds are allowed to absorb moisture to a point just prior to germination. After this period, seeds are dried to their original moisture content and stored before sowing. Pretreated seeds exhibit earlier initiation of protein, RNA, and DNA synthetic activity when rehydrated for subsequent germination compared with untreated seeds. The RNA and proteins that are synthesized during early imbibition, including DNA polymerase, remain stored and undegraded from the preimbibition period through the dehydration phase. As a consequence, when the seed is set out for germination, cellular events are much advanced (Sen-Mandi et al 1995). Seed priming with water (Harris et al 1999), chemical (Jeyabal and Kuppuswamy 1998), and fertilizer solutions (Rao et al 1981, Thakuria and Choudhary 1995, Thakuria and Sarma 1995) has been used to improve seedling establishment of other crops but its effects on DS rice have not been investigated adequately.

The degree of weed infestation in dry-seeded rice depends on the hydrological conditions of the field at the time of seeding and on tillage activities (Bhagat et al 1999). Time of seeding may therefore influence weed infestation in dry-seeded rice because field hydrology changes with seeding dates (Tuong et al 2000b). Rice farmers in the Mekong Delta, Vietnam, who practice dry seeding often do primary tillage very early—at the onset of the rainy season. Secondary tillage (harrowing) buries seeds further and is carried out immediately after seeding (My et al 1995). We hypothesize that late seeding may have less weed infestation because weeds that emerge after primary tillage may be controlled by the subsequent harrowing. Late seeding, however, may expose seeds to submergence and reduce their plant stand (Naklang 1997).

To combat weed infestation, farmers in the Mekong Delta plant dry-seeded rice at a high density of up to 600 seeds m^{-2} (My et al 1995). A plant density that is too high, however, may lead to increased early dry matter production but reduced grain yields (Tuong et al 2000b). A high seed rate also has a production cost implication to farmers. We postulated that a high seed rate could be avoided if seed priming and seeding time were adopted to improve crop stand establishment of dry-seeded rice.

This study was carried out to test the hypothesis that seed priming, seeding rate, and seeding time can improve crop establishment and enhance weed suppression and grain yield of DSR in the Mekong Delta. Field experiments were carried out to quantify rice seedling germination, rice and weed growth dynamics, and yields of dry-seeded rice crops that were established with various priming treatments and seed rates under different agrohydrological conditions at a rainfed lowland site in Vietnam. Findings would contribute to identifying options to improve the productivity of dry-seeded rice systems elsewhere.

Materials and methods

Experimental site

We conducted the study at Binh Chanh District (10.75° N, 106.58° E), Ho Chi Minh City, Vietnam. Soil at the experimental site can be classified as a Sulfate Typic Tropaquept (Soil Survey Staff 1992). The 0–20-cm soil layer had more than 60% clay content and was slightly acid. The average annual rainfall at the site ranged from 1,500 to 1,900 mm, of which more than 90% fell during the wet season from May to November.

Experimental layout

We conducted two experiments—the first one from 20 May to 30 August 1998 and the second from 9 May to 1 September 1999. Both years used a split-split plot design with four replications, a sub-subplot size of 4 × 6 m, and rice cultivar OMCS94.

The 1998 experiment

Main plots consisted of two seeding dates: early seeding (T_1) on 20 May and late seeding (T_2) on 29 May. Subplots were two hand-weeding treatments: early weeding (W_1) at 30 d after emergence (DAE) and late weeding (W_2) at 45 DAE. Originally, early weeding was planned for 15 DAE but a severe drought on 12–20 June, at about 15 DAE of the first seeding, made hand weeding impossible in a dry and hard soil condition. Sub-subplots consisted of five seed priming treatments:

- SP_0: unprimed (control)
- SP_{KCl}: seeds were primed with 4% KCl solution
- SP_{CaHPO_4}: seeds were primed with saturated $CaHPO_4$ solution
- SP_{NPK}: seeds were primed with 4% solution of 7-13-34 NPK
- SP_{H_2O}: seeds were primed with water

In all priming treatments, seeds were soaked in priming solutions for 15 h (overnight) at room temperature (27–29 °C), then sun-dried for 1–2 d to the original moisture content (14%). Primed seeds were prepared 4 d before each seeding date. Priming solutions and priming procedures were based on findings of previous researchers (Lee et al 1998, Harris et al 1999, Jeyabal and Kuppuswamy 1998, Rao et al 1981, Thakuria and Choudhary 1995, Thakuria and Sarma 1995). In all treatments, seeds were broadcast at 160 kg ha^{-1}, an average dry-seeding rate in the Mekong Delta (My et al 1995).

The 1999 experiment

Treatments in 1999 were modified based on 1998 results. In the main plots, the number of seeding dates was increased to three for a wider range of hydrological conditions at seeding and in the crop establishment period. Originally, the first seeding date was planned at the end of April to expose seedlings to early season drought. Unfortunately, heavy rains on 23 and 24 April 1999 prevented early dry seeding. The three seeding dates were adjusted to 9 May (T_1), 16 May (T_2), and 23 May (T_3).

In the subplots, in place of weed control treatments, we included seeding rate treatments (D_1: 80 kg ha^{-1} and D_2: 160 kg ha^{-1}). To highlight weed suppression in different treatments, experimental plots were left unweeded. Sub-subplots included the unprimed seed treatment (S_0) and two priming treatments, SP_{KCl} and SP_{CaHPO_4}.

Cultural practices

Primary tillage was carried out by rototilling with a four-wheel tractor after a few light rains at the onset of the rainy season on 17 May 1998 (3 d before first seeding) and 20 April 1999 (20 d before first seeding). In the farmer's field, the second rototilling was carried out using a four-wheel tractor right after seeding to further pulverize soil clods and to bury the seeds (My et al 1995). In our experiment, we replaced the second rototilling by hand raking be cause of the small size of the experimental plots.

A basal dose of 80 kg ha^{-1} of P_2O_5 and K_2O was applied before each seeding. Nitrogen (90 kg ha^{-1} in 1998 and 160 kg ha^{-1} in 1999) was applied in four equal topdressed splits at 15, 30, 45, and 60 DAE. In the first seeding of 1998, however, the first N application was delayed until 21 June (31 DAE) because of droughts that occurred on 29 May–9 June and 12–20 June. We increased the rate of N fertilizer in 1999 to ensure that nutrient was not a yield-limiting factor.

Soil and water monitoring

Rainfall and evaporation were recorded daily at the experimental site. Soil moisture content was monitored twice a week, from the first seeding until the field became permanently flooded. Soil samples were taken using undisturbed cores at 0–5-, 5–10-, and 10–20-cm depths, from three random locations in each main plot. From the fresh and oven-dried weight of samples, the soil moisture content was expressed in percentage on a volumetric basis. Groundwater depth was monitored daily at one location per main plot, using 2-cm-diam PVC tubes perforated from 0.5 to 2.5 m and installed to a depth of 2.5 m (Tuong et al 2000b).

Rice and weed monitoring

The number of newly emerged and dead seedlings (i.e., seedlings that emerged successfully but died afterward) was monitored daily in two 0.5×0.5-m quadrats in each sub-subplot from seeding until seedlings died. The emergence percentage was expressed as the ratio between cumulative emerged seedlings and total seeds sown. The established plant density (plants m^{-2}) was calculated from the difference between the number of final cumulative emerged seedlings and the number of final cumulative dead seedlings. Rice plants in the same frames were also used to determine tiller numbers (at 30 and 80 DAE in 1998 and at 15, 30, 45, and 80 DAE in 1999) and yield components at maturity.

In 1998, weeds were sampled for weed dry weight determination at 30 DAE (for the early treatment, W_1) and 45 DAE (for W_2) from two 1×1-m quadrats in each sub-subplot. In 1999, weeds were sampled by the same procedure at 15, 30, and 75 DAE. The total biomass of rice (1999 only) at 30 DAE and 45 DAE and at harvest was determined from two 0.2×0.2-m quadrats. Rice yields (adjusted to 14% moisture) were determined from 2.5×2-m harvest areas at the center of sub-subplots.

Results and discussion

Agrohydrological conditions

The rainfall and groundwater depth during seeding and crop establishment of experiments in 1998 and 1999 are presented in Figures 1A and 2A, respectively. In 1998, dry spells from 29 May to 9 June and 12–20 June reduced the soil moisture content of the 0–5-cm soil layer by 22–25% (about the wilting point). During May and early June, groundwater fluctuated within a 150-cm depth. The soil surface became submerged after 25 June 1998. In 1999, relatively higher soil moisture content persisted during periods between three seeding dates (Fig. 2A) because of heavy rains on 23 and 24 April (110 mm) and subsequent rains, which raised the groundwater above the soil surface until 4 May. Groundwater depth was within 30 cm from the soil surface in May. Two drought spells occurred on 16–29 June and 1–8 July (data not shown).

Seedling emergence and established plant density

Figures 1B and 2B show the time course of cumulative seedling emergence of DS rice in 1998 and 1999, respectively. In the first seeding of the 1998 experiment, seedling emergence was delayed until 7 d after seeding (DAS). In the second seeding, seedlings started to emerge at 5 DAS. The emergence rate (i.e., slope of cumulative emergence curves) of the second seeding in 1998 was lower than that of the first seeding. The delay in emergence during the first seeding was probably caused by low soil moisture content at seeding. Similarly, the low emergence rate in the second seeding was attributed to low soil moisture content (about 22%, Fig. 1A) during the 29 May–9 June dry spell.

In 1999, the final emergence percentage of the second and third seeding was considerably less than that of the first seeding and of the 1998 seedings. High soil moisture (near or at the saturation point) and frequent rainfall after the second and third seeding in 1999 must have affected the emergence of dry-seeded rice.

Figure 3 shows the established plant density and final cumulative number of dead seedlings m^{-2} in the two seeding dates of 1998. The number of dead seedlings in the second seeding (from 20 to 40 seedlings m^{-2}) was higher than in the first seeding (5 to 15 seedlings m^{-2}). This was due to the 29 May–9 June drought, which occurred during early emergence in the second seeding. By that time, the root systems of established plants in the first seeding had grown deeper into the soil, helping plants avoid the damage caused by the drought. In 1999, the number of seedlings that died during emergence was negligible (<10 seedlings m^{-2}, data not shown) in all seeding dates and priming treatments. This was because the seedlings did not suffer from any drought (Fig. 2B).

The second seeding in 1998 had a lower cumulative percentage (Fig. 1B) and a higher number of dead seedlings (Fig. 3) than the first seeding. Consequently, the mean established plant density (310 plants m^{-2}) of the first seeding was significantly lower than in the second seeding (370 plants m^{-2}). The established plant density was greatly affected by hydrological conditions at seeding as well as during the emergence of dry-seeded rice.

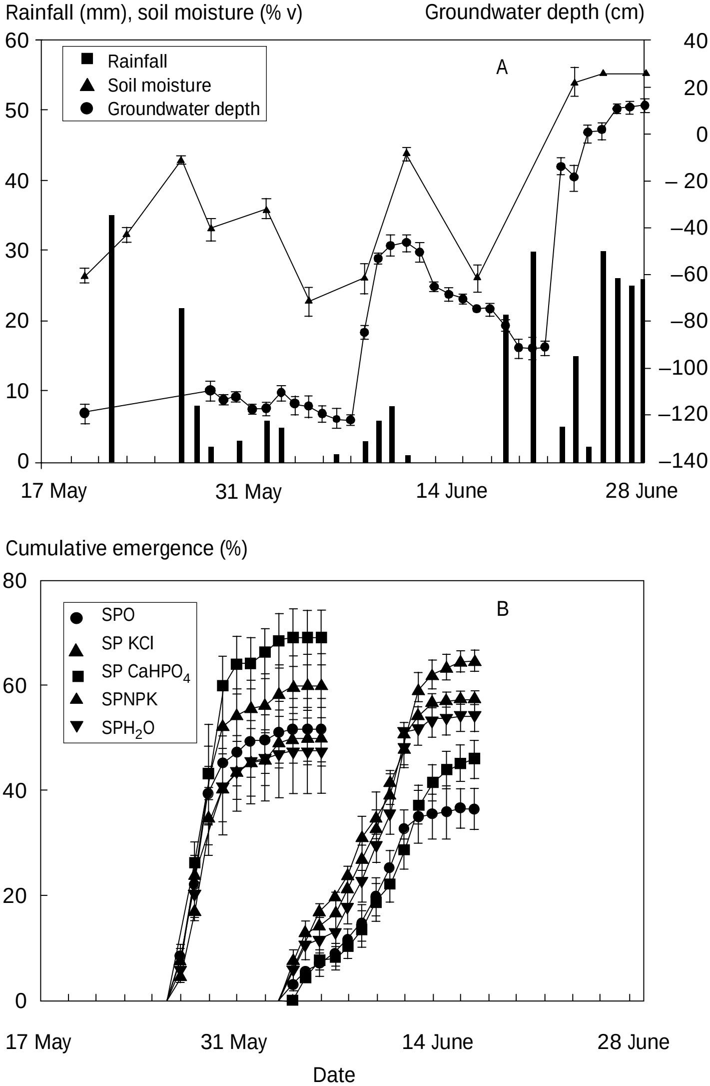

Fig. 1. (A) Rainfall, groundwater depth (means of 4 replications), and soil moisture of 0–5-cm layer (means over 2 seeding dates, 4 replications, and 3 locations per replication) and (B) emergence percentage (means of 4 replications) of dry-seeded rice cv. OMCS94. SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO4} = with saturated $CaHPO_4$ solution; SP_{NPK} = with 4% NPK 7-13-34 solution; SP_{H2O} = with water; T_1 = seeding on 20 May; T_2 = seeding on 30 May. Ho Chi Minh City, 1998. Standard errors are shown for each mean value of soil moisture content and groundwater depth.

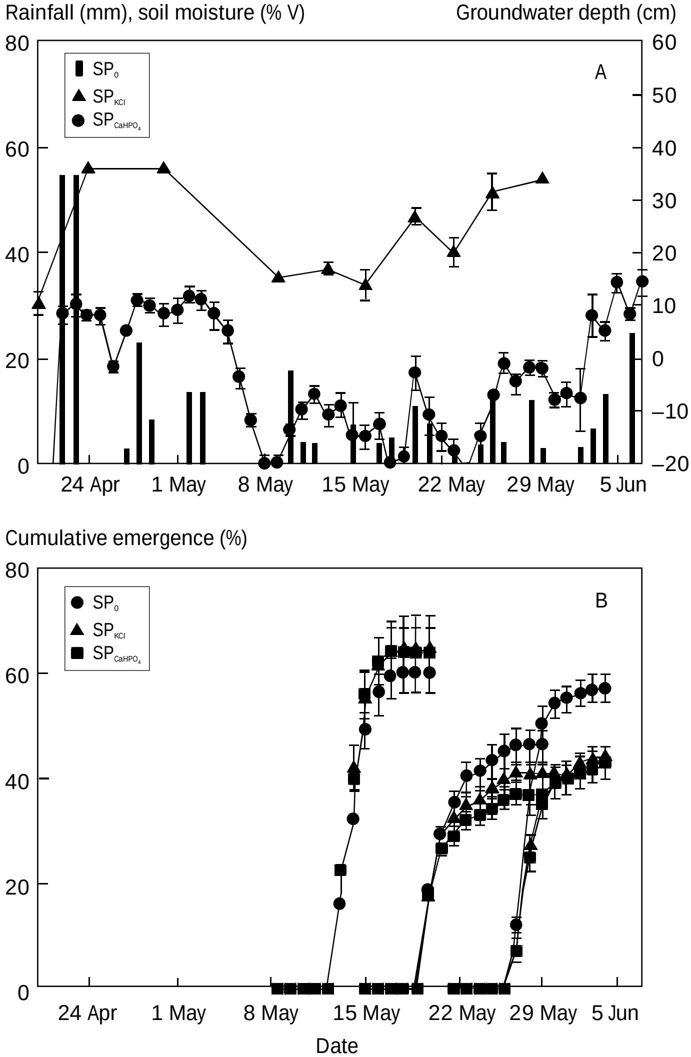

Fig. 2. (A) Rainfall, groundwater depth (means of 4 replications), and soil moisture of 0–5-cm layer (means over 3 seeding dates, 4 replications, and 3 locations per replication) and (B) emergence percentage (means of 2 seeding rates, 4 replications) of dry-seeded rice cv. OMCS94. SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; T_1 = seeding on 9 May; T_2 = on 16 May; T_3 = on 23 May. Ho Chi Minh City, 1999. Standard errors are shown for each mean value of soil moisture content and groundwater depth.

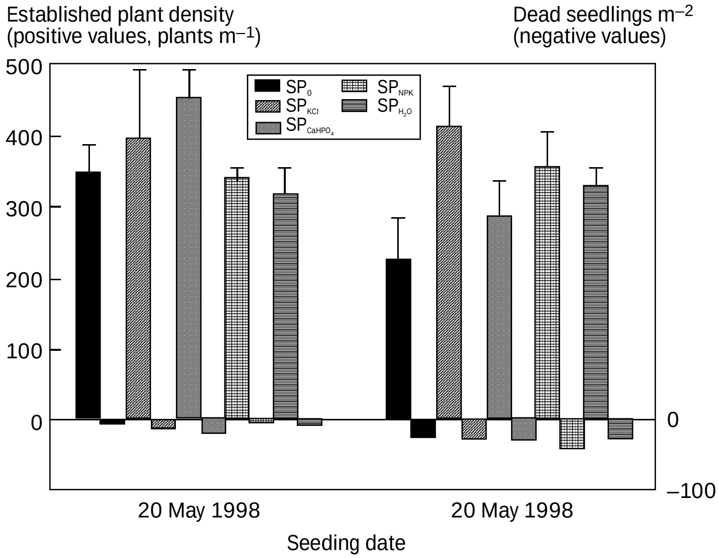

Fig. 3. Established plant density (positive values) and dead seedlings (negative values) (means of 2 samples over 4 replications). SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; SP_{NPK} = with 4% NPK 7-13-34 solution; SP_{H_2O} = with water. Ho Chi Minh City, 1998. Standard errors are shown for each mean value of established plant density and dead seedlings.

Priming treatments SP_{KCl} and SP_{CaHPO_4} enhanced emergence rate and increased the final emergence percentage compared with the control in both 1998 seedings ($P < 0.05$, Fig. 1B) and in the first seeding of 1999 ($P > 0.05$, Fig. 2B). In 1998, SP_{NPK} and SP_{H_2O} also had the same effects but they were significant only in the second seeding (Fig. 1B). Conversely, SP_{KCl} and SP_{CaHPO_4} significantly reduced the final emergence percentage of the second and third seeding in 1999 compared with the unprimed treatment (Fig. 2B).

In both years, priming treatments did not have any significant effect on the number of dead seedlings. The latter was negligible compared with the percentage of seedling emergence. The effect of priming treatments on the progress of seedling emergence was similar to their effects on the resulting established plant density.

The effects of priming on emergence and established plant stand thus varied with priming solution and hydrological conditions at seeding and during emergence. Priming enhanced emergence and established plant stand when seeding and emergence took place under relatively low soil moisture content (as in 1998 and the first seeding of 1999). The positive effect of priming seemed to be more pronounced under drought conditions: the effect in the second seeding of 1998 was more noticeable than in the first seeding and this, in turn, was more noticeable than in the first seeding of 1999. In contrast, priming suppressed emergence and established plant stand when seeding was carried out at or near saturation, as in the second and third seeding in 1999.

In the 1999 experiment, established plant density also depended on seeding rate. The higher seeding rate resulted in a higher established plant density (Fig. 4).

Rice tiller number

Table 1 shows the final tiller number in the 1998 experiment and Figure 5 presents the dynamics of tiller number in the 1999 experiment. In the first seeding of 1998, rice in the late weed control treatment had significantly fewer tillers than in the early weed control treatment. In contrast, weed control treatments did not affect rice tiller number in the second seeding (Table 1). The different effects of weeding on final tiller number between the two seedings were probably caused by the more severe weed infestation in the first seeding (see below).

In 1999, tiller number of the high seeding rate treatment was consistently higher than that of the low seeding rate treatment until 45 DAE. Maximum tiller number in the first seeding was significantly higher than in the second and third seeding (Fig. 5). The higher maximum tiller numbers in the first seeding and in treatments with a higher seeding rate corresponded with a higher established plant density (Fig. 4). High tiller abortion in the first and second seeding resulted in no significant difference in final tiller numbers between the second and third seeding. The difference in

Table 1. Final tiller numbers (tillers m^{-2}) of dry-seeded rice cv. OMCS94 as influenced by date of seeding, weed control, and seed priming treatments.

Seeding date and priming treatment[a]	Early weeding (at 30 DAE)	Late weeding (at 45 DAE)	Difference[b]
20 May 1998			
SP_0	578 c[c]	362 b	216**
SP_{KCl}	865 a	456 a	409**
SP_{CaHPO_4}	756 b	414 ab	342**
SP_{NPK}	737 b	381 ab	356**
SP_{H_2O}	710 b	399 ab	311**
Mean	707	402	305**
29 May 1998			
SP_0	333 b	338 b	–5 ns
SP_{KCl}	380 ab	385 ab	–5 ns
SP_{CaHPO_4}	355 b	378 ab	–23 ns
SP_{NPK}	396 ab	412 a	–16 ns
SP_{H_2O}	343 b	383 ab	–40 ns
Mean	361	379	–18 ns

[a]SP_0 = unprimed, SP_{KCl} = seeds primed with 4% KCl solution, SP_{CaHPO_4} = with saturated $CaHPO_4$ solution, SP_{NPK} = with 4% NPK 7-13-34 solution, SP_{H_2O} = with water. DAE = days after emergence. [b]Significant at the 1% level, ns = not significant. [c]Means followed by the same letters do not differ significantly at the 5% level.

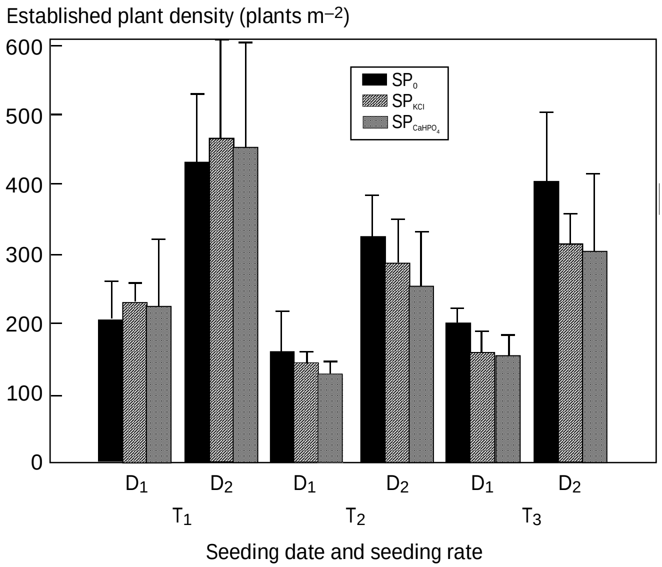

Fig. 4. Established plant density (means of 2 samples over 4 replications). SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; T_1 = seeding on 9 May; T_2 = on 16 May; T_3 = on 23 May; D_1 = seeding rate 80 kg ha^{-1}; D_2 = 160 kg ha^{-1}. Ho Chi Minh City, 1999. Standard errors are shown for each mean value of established plant density.

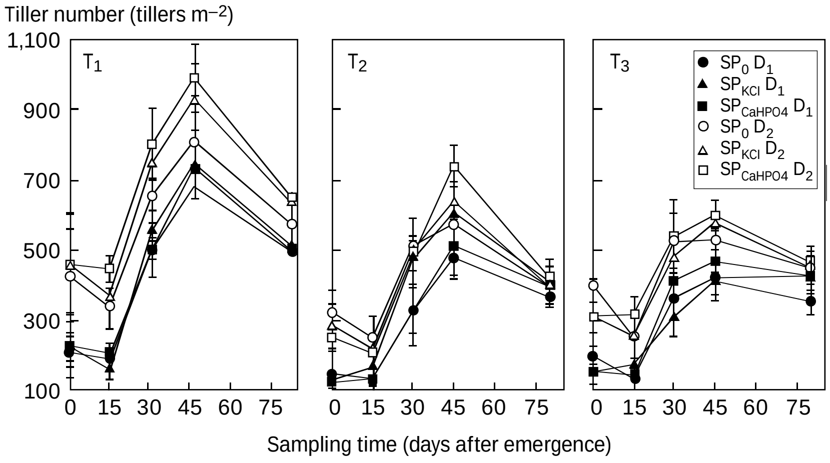

Fig. 5. Tiller number (means of 4 replications). SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; T_1 = seeding on 9 May; T_2 = on 16 May; T_3 = on 23 May; D_1 = seeding rate 80 kg ha^{-1}; D_2 = 160 kg ha^{-1}. Ho Chi Minh City, 1999.

final tiller number between the two seeding rates also became insignificant in the second and third seeding.

In general, final tiller number in the primed treatments in 1998 (Table 1) was higher than that of the unprimed treatment. The level of significance of differences between the control and primed treatments, and among primed treatments, varied with the seeding date and weed control treatments. Treatments with a higher established plant stand did not necessarily have higher final tiller numbers. For example, in the first seeding, the unprimed treatment had a higher plant stand density than SP_{H_2O} (Fig. 3) but the latter had more final tillers than the control.

In 1999, there was a strong interaction between seed priming and seeding date treatments as shown by maximum tiller number. Treatment SP_{CaHPO_4} significantly increased maximum tiller number in the second seeding compared with SP_0 and SP_{KCl}, but there was no significant difference among seed priming treatments in the third seeding. The final tiller number in primed seed treatments was generally higher than in the control treatment, although it was significant only in the first seeding at the higher seeding rate.

In summary, the effect of primed treatments on final tiller numbers was different from that on established plant density. Priming can affect both the number of successfully established seedlings and their size or vigor, and thus the subsequent ability of the plant to extract and allocate resources in subsequent seasonal conditions. The effect of priming on the seedling vigor of dry-seeded rice was not quantified in our study and warrants further investigation.

Weed dry weight

In the 1998 experiment, the first seeding had a higher weed dry weight than the second seeding, but the difference was significant only for samples at 35 DAE (Fig. 6). Weed dry weight in 1999 (below 25 g m^{-2}; Fig. 7) was considerably less than that

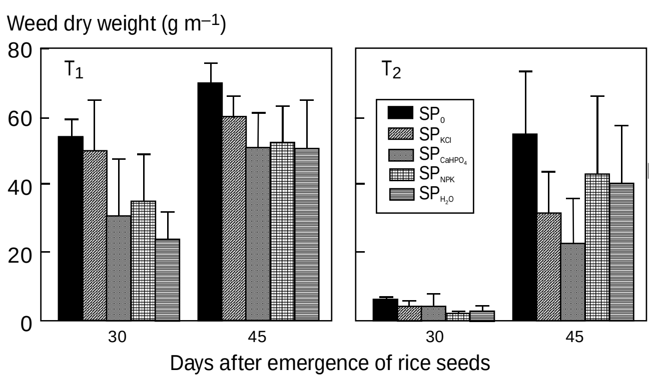

Fig. 6. Weed dry weight (means of 4 replications). SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; SP_{NPK} = with 4% NPK 7-13-34 solution; SP_{H_2O} = with water; T_1 = seeding on 20 May; T_2 = on 30 May. Ho Chi Minh City, 1998.

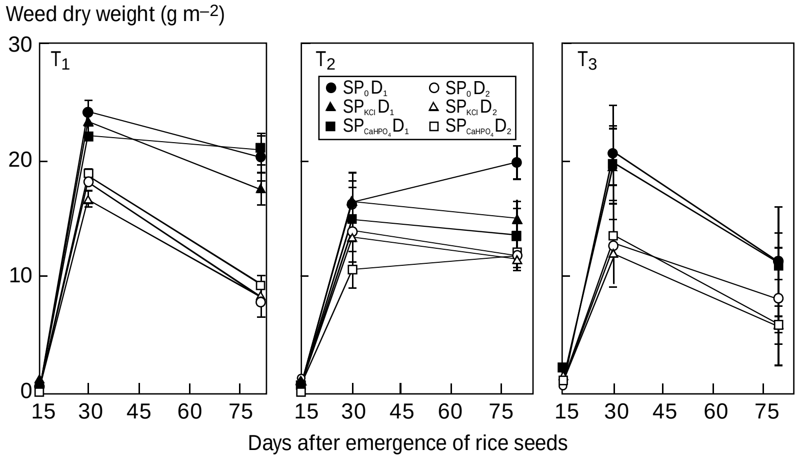

Fig. 7. Weed dry weight (means of 4 replications). SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; T_1 = seeding on 9 May; T_2 = on 16 May; T_3 = on 23 May; D_1 = seeding rate 80 kg ha^{-1}; D_2 = 160 kg ha^{-1}. Ho Chi Minh City, 1999.

in the first seeding of 1998. The rather long delay (13 d in the second seeding in 1998 and 20–34 d in 1999) and adequate moisture between primary rototilling and rice sowing probably allowed the weeds to emerge before rice sowing. The weeds may have been eliminated by raking, which followed immediately after rice sowing. In the first seeding of 1998, the low soil moisture content and short duration (3 d) between rototilling and rice sowing prevented weeds from emerging before rice sowing; thus, raking did not have any effect on weed control. Results supported the findings of Bhagat et al (1999), which showed that duration between tillage activities had more effect on weeds than tillage intensity itself, especially if the soil was wet or it rained, allowing weeds to emerge in between tillage activities.

A higher seeding rate in general reduced weed dry weight compared with a low seeding rate (Fig. 7), but the difference was significant only in the first seeding and at 35 DAE in the third seeding. Treatments with higher tiller numbers tended to have a lower weed dry weight. This agrees with results of previous studies (Tuong et al 2000a).

In both years, the difference in weed dry weight among priming treatments was not significant at the 5% level (Figs. 6 and 7), except for the second seeding, which has a low seeding rate, where SP_0 had a significantly higher weed dry weight than the primed treatments.

Grain yield

In 1998, mean rice grain yields ranged from 2.3 to 3.7 t ha^{-1} (Fig. 8). In the first seeding, yield in plots with early weed control was significantly higher than in plots with late weed control. The difference in yield between the two weed control treat-

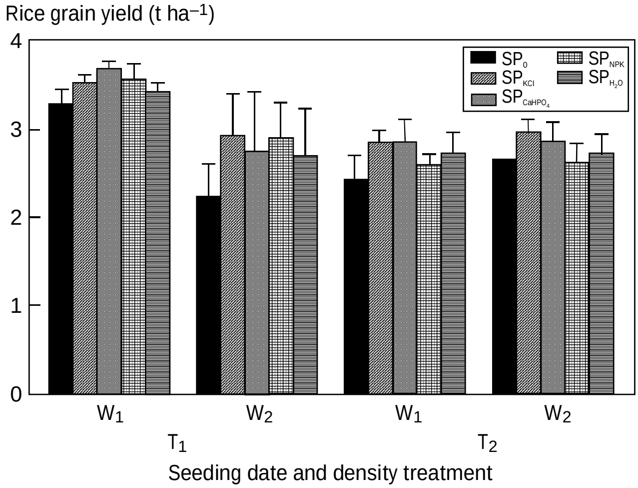

Fig. 8. Rice grain yield (means of 4 replications). SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; SP_{NPK} = with 4% NPK 7-13-34 solution; SP_{H_2O} = with water; T_1 = seeding on 20 May; T_2 = on 30 May; W_1 = weeding at 30 DAE; W_2 = at 45 DAE. Ho Chi Minh City, 1998.

ments was not significant in the second seeding. Early weeding was necessary to maintain yield when weed infestation was high (as in the first seeding), but not under low weed infestation conditions (in the second seeding, Fig. 6).

In the 1999 experiment, a higher seeding rate gave a higher yield than the low seeding rate in the second and third seeding, but not in the first seeding (Fig. 9). Increasing the seeding rate in the second and third seeding allowed plant density to increase beyond a critical level (about 200 plants m^{-2}, Fig. 4) that was needed to intercept resources and compete effectively with weeds for resources. In the first seeding, the established plant density was adequate with a lower seeding rate.

The effect of seed priming on final yield differed between years. In 1998, primed seed treatments gave a higher yield than the unprimed seed treatment in all seeding dates and weed control treatments (Fig. 8). Averaged over the two seeding dates and weed control treatments, the yield differences between SP_0 and the primed treatments were significant ($P < 5\%$). Treatments SP_{KCl} and SP_{CaHPO_4} gave the significantly highest yields. In 1999, the effects of seed priming were inconsistent at different seeding dates and seeding rates. In the first seeding, seed priming increased rice yield slightly, but, in the second and third seeding, it sometimes suppressed rice yield compared with the control (Fig. 9). In all 1999 seedings, the difference in yield was not significant at the 5% level. The positive effect of seed priming on grain yield in 1998 was consistent with an increase in final tiller number (Table 1), which was associated with a suppression of weed dry weight (Fig. 6).

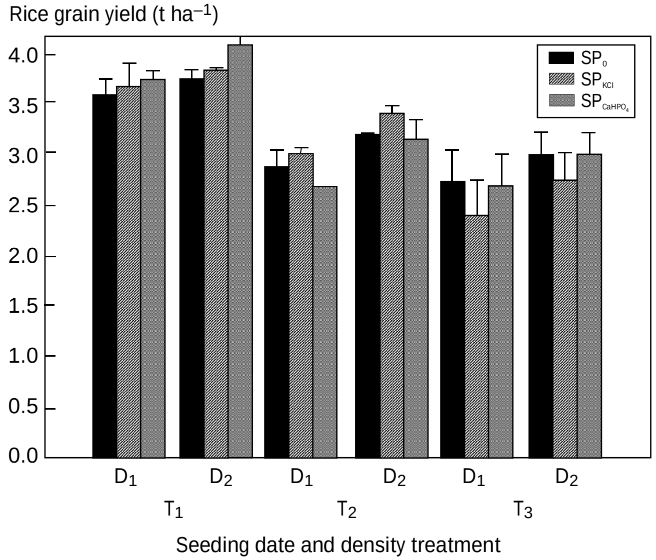

Fig. 9. Rice grain yield (means of 4 replications). SP_0 = unprimed; SP_{KCl} = primed with 4% KCl solution; SP_{CaHPO_4} = with saturated $CaHPO_4$ solution; T_1 = seeding on 9 May; T_2 = on 16 May; T_3 = on 23 May; D_1 = seeding rate 80 kg ha^{-1}; D_2 = 160 kg ha^{-1}. Ho Chi Minh City, 1999.

Conclusions

Seed priming, especially with 14% KCl solution and saturated $CaHPO_4$, can enhance crop emergence, increase established plant density, increase tiller number, and lead to an increase in yield of dry-seeded rice when seeds are sown under low soil moisture content and drought during crop establishment. Priming, however, suppresses crop establishment when soil moisture (near or at saturation) is high at seeding and during emergence, and may lead to some decrease in final yields. Seed priming treatments did not influence weed dry weight during crop growth. Stale seedbeds, associated with late seeding, reduced weed infestation. When the established plant density was low, increasing the seeding rate resulted in greater established plant density beyond a critical level (about 200 plants m^{-2}) that was needed to intercept resources and compete effectively with weeds, and increased yield. Increasing the seed rate offered little benefit when the established plant density was already high.

Seed priming with appropriate chemicals can be an effective option to cope with erratic rainfall when seeding has to be carried out early and seeds are likely to be exposed to droughts. It can reduce the need for using a high seeding rate to establish an adequate crop stand density. Stale seedbeds may reduce weed infestation but a delay in seeding may also expose seeds to high soil moisture, leading to reduced germination. Late seeding may also delay harvest and affect the timing of the following crop. Priming may be detrimental in late seeding when seeds are sown under high soil moisture conditions. Further research is needed to investigate the effect of seed priming on seedling vigor and on the ability of established seedlings of dry-seeded rice to extract and allocate resources in subsequent seasonal conditions.

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Notes

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Rice cultivar requirements for direct seeding in rainfed lowlands

S. Fukai

This paper reviews the performance of rice genotypes established from direct seeding in rainfed lowlands. It attempts to determine plant types that are suitable for this rice cropping system.

The paper first describes growth and yield of crops established from transplanting and direct seeding. Direct seeding, particularly broadcasting, often enables seeding early in the season with high established plant density and consequently higher yield compared with transplanting. However, establishment from direct seeding may be affected by adverse conditions such as submergence and drought, particularly in the rainfed lowland ecosystem where water control is limited. Problems with weeds and lodging are common in direct-seeded fields and yields can be greatly affected. As a result, yield variation tends to be larger under direct seeding.

The next section describes cultivar requirements for rainfed lowland rice under direct seeding. Crop establishment is important particularly for direct-seeded rice, and the ability to germinate and emerge under a wide range of moisture conditions is required. There are notable genotypic differences in seedling vigor and submergence tolerance. Semidwarf genotypes do not commonly have strong vigor, but some genotypes are vigorous and appear to be promising as they also have high yield potential. Photoperiod-insensitive cultivars with high yield potential appear to be suitable for direct-seeded rice under diverse growing conditions. Short-duration rice cultivars seem to be more affected by weeds because of poor competitiveness or the inability to recover from the adverse effect of weeds. Traditional, tall, long-duration cultivars could compete against weeds better. However, they are unsuitable for direct seeding if they are prone to lodging under high density and shallow planting conditions. The ideal plant type that can strongly compete against weeds has shoots that spread and cover the ground rapidly during the vegetative stage, but, with the onset of panicle initiation, these shoots will not dominate reproductive organ development.

In addition to these specific requirements for direct seeding, there are also more general genotypic requirements for rainfed lowland rice. The key point is adaptation to adverse water conditions, either drought or submergence. There is a trade-off between high potential yield under favorable conditions and adaptation to adverse water conditions. Therefore, the ideal cultivar type for direct-seeded rainfed lowland rice is largely determined by target environmental conditions; therefore, identification of environmental conditions is required.

Several studies have compared the yield of rainfed lowland rice established from direct seeding with that from transplanting. Under favorable water availability conditions in Thailand, crops established from dry-seeded broadcasting produced a higher yield than those from transplanting because of higher plant density when establishment was successful, but produced a lower yield when crop establishment problems occurred (Naklang et al 1996, Naklang 1997). In a survey of yield in more than 100 farmers' fields in northeast Thailand, the two establishment methods produced similar yields in 1995 when rainfall was generally high (Miyagawa et al 1998). However, in 1994, when rainfall was lower, yield was lower under direct seeding, particularly on farms in drought-affected areas. The yield component analysis revealed that a smaller number of spikelets per panicle was responsible for lower yield under direct seeding in that year (Miyagawa et al 1998). For the whole northeast Thailand, where rainfed lowland is the most common rice production system, mean yield in 1989-92 was 1.8 and 1.4 t ha^{-1} for transplanted and dry-seeded broadcast rice, respectively (Naklang 1997, Table 1). Direct-seeded area increased rapidly in the late 1980s and rice areas established from transplanted and dry-seed broadcast were 73.6% and 25.5%, respectively, in 1992. Thus, one of the reasons for the lack of yield improvement in recent years in northeast Thailand was the expansion of area under direct seeding, which produced lower yields than transplanting. One reason for the low yield of direct-seeded rice is that existing cultivars may not be suitable for direct seeding because they were developed under transplanted conditions.

Table 1. Total rice planted area, percentage of differing establishment methods, and average grain yields in northeast Thailand, 1992.

Establishment method	Percentage	Yield (t ha^{-1})
Transplanted	73.6	1.8
Dry-seeded, broadcast	25.5	1.4
Germinated seed, broadcast	0.3	1.8
Dibbling	0.7	1.4
Total area (million ha)	5.1	1.7

Source: Naklang (1997).

The objective of this paper is to review recent work on genotypic characters required for rainfed lowland rice. However, direct seeding of rice is practiced under irrigated conditions in many countries, and understanding cultivar requirements under irrigated conditions is relevant for rainfed lowland rice, and is thus included in this review.

Growth of rice crops established from direct seeding and transplanting

Crop establishment from either direct seeding or transplanting is one of the most critical cultural practices that greatly affect subsequent growth, development, and yield of rice. In this section, the effects of changing from transplanting to direct seeding on rice growth are described.

Early seeding

One aspect of transplanting in rainfed lowlands is that farmers tend to delay seeding in the nursery until some time after the start of the rainy season, when they believe that soil moisture is sufficient for transplanting. This delay tends to expose the crop to late-season drought if the cultivars used are photoperiod-insensitive and hence mature late in the season. If the cultivars used are photoperiod-sensitive, their growing duration is shortened, with a consequent reduction in potential grain yield (Fukai and Cooper 1995). The cultivars selected for transplanting tend to be adapted for late seeding. Different cultivar types may be required for direct seeding, which tends to take place early in the season, with a potentially longer growing duration. For example, late-season terminal drought is common in drought-prone rainfed lowlands (Jongdee et al 1997) and cultivars resistant to late-season drought are required. However, this may not be so for direct seeding, in which crops are sown early in the season.

Seeding early in the season may result in seedlings experiencing early season drought. If photoperiod-sensitive cultivars are seeded early in the season, they grow for a longer period before flowering and they may lodge, particularly if soil fertility is high. When seeded early in the season, short-duration photoperiod-insensitive cultivars will flower in the middle of the wet season, high rainfall could reduce the chance of successful fertilization, and the crop could be exposed to rodents. Seeding early in the season is also often associated with inadequate time for land preparation and weeds are commonly a greater problem.

Difficulty in crop establishment

Unlike a seedling nursery, which is generally located at a favorable and protected site on the farm, a direct-seeded crop in the field grows under more difficult crop establishment conditions. This leads to a higher risk of poor establishment. Although transplanting is usually successful as long as there is standing water, direct seeding in rainfed lowlands often requires more precise soil moisture conditions for good crop establishment. Because direct-seeded rice plants take longer to reach a certain height than transplanted plants, they may have more problems with flooding during early growth stages (Miyagawa et al 1998). Other problems such as drought, salinity, crabs, birds, rats, and weeds are also more common among seedlings established from direct seeding. Some of the problems are reduced if seeds are planted deeper in the soil (Yamauchi 1995). Cultivars for direct seeding need to be more tolerant of adverse conditions than those for transplanting. One particular problem in rainfed lowlands is unleveled land, which makes it more difficult to have an even crop establishment across fields, particularly under direct seeding (CIAP 1998). Seedlings in some parts of the field may be submerged, whereas those in other parts may be water-stressed.

Planting depth varies greatly in direct seeding, depending on land preparation, soil type, and planting method used. Shallow planting is common, particularly under broadcasting. This may cause an establishment difficulty under dry conditions, and it could also make plants more susceptible to lodging later in their life cycle. However, if seeds are placed at shallower depths, rice seedlings may not be able to emerge and crop establishment may be poor (Yamauchi 1995). Cultivar differences in crop establishment are discussed in the next section.

In direct seeding, there is no temporary cessation of growth caused by transplanting, and hence tillering and other growth processes continue without any transplanting shock (Dingkuhn et al 1990). Thus, cultivars with a capacity for good tillering may not be required for direct-seeded rice. Without transplanting shock, direct-seeded crops also mature earlier. Therefore, Dingkuhn et al (1990) suggested that, for direct-seeded rice under irrigated conditions, cultivars with shorter growth duration are required. This may not necessarily be the case in rainfed rice, where short-duration cultivars may be affected more by competition with weeds.

High plant density

Compared with transplanting, direct seeding, particularly broadcasting, will result in higher established plant density under favorable growing conditions. This is related to the larger amount of seeds used for direct seeding, which is 80–100 kg ha^{-1}. This has many implications for subsequent crop growth. Usually, there would be more tillers per unit area (Dingkhun 1992a,b, Schnier et al 1990). This may result in a larger number of panicles and, hence, higher grain yield, particularly when water availability during growth is favorable (Naklang et al 1997). Panicle number is the yield component responsible for increased yield in plant density experiments conducted by Miller et al (1991).

High biomass as a result of high established plant density, however, requires a larger amount of nutrients, and direct-seeded crops may run out of nutrients during crop growth under irrigated conditions (Dingkhun et al 1992a,b, Schnier et al 1990). Leaf N concentration decreased faster in direct-seeded rice. Also, the rate of canopy photosynthesis declined faster and leaves started to senesce earlier in direct-seeded rice than in transplanted rice (Dingkhun et al 1991). Topdressing of N resulted in increased grain number per panicle and grain yield in direct-seeded rice (Dingkhun et al 1991). In irrigated rice crops in both the wet and dry seasons, crop growth rate and N uptake rate were higher in direct seeding during early stages, but they were lower during grain filling, particularly when no N was applied (Peng et al 1996). Results may be different under rainfed lowland conditions, however, in which N may be lost more easily with an alteration of saturated and unsaturated soil water conditions, and N uptake may cease early during crop growth (Inthapanya et al 2000).

The harvest index of direct-seeded rice is often lower than that of transplanted crops (Peng et al 1996, Miyagawa et al 1998), perhaps because of higher plant density. Thus, cultivars required for direct seeding are those that are able to maintain a high harvest index. When plant density is increased, yield also increases. However, high density often results in taller plants with thin stems that cause the plants to lodge. The requirement for lodging resistance is discussed later.

Specific genotypic characters required for direct seeding

A few characters are specifically required under direct seeding for rainfed lowland rice (Mackill and Redoña 1997). These characters are associated with direct-seeding conditions and include photoperiod insensitivity, good competitive ability against weeds, seedling vigor including submergence tolerance, and lodging resistance (Table 2).

Photoperiod insensitivity

A common problem in transplanted rice culture in the rainfed lowlands is a delay in transplanting because of a lack of standing water in the main field, and hence the use of old seedlings for transplanting. Cultivars with photoperiod sensitivity are often preferred for transplanting because the adverse effect of using old seedlings on yield is less than with photoperiod-insensitive cultivars (Mackill et al 1996). The require-

Table 2. Major factors that differentiate cultivar preferences for transplanting and direct seeding (broadcasting). Changes in characteristics with the adoption of direct seeding and reasons for such changes are also shown.

Factor	Transplanting	Direct seeding	Reasons for change
Photoperiod	Sensitive	Insensitive	Elimination of the use of old seedlings for transplanting Early seeding
Tillering capacity	Higher	Lower	High planting density No transplanting shock
Lodging resistance	Lower	Higher	High planting density Shallow planting
Seedling vigor	Lower	Higher	Exposed to adverse conditions after seeding Higher chance of submergence in water
Competitiveness against weeds	Lower	Higher	Establishment difficulty Lack of standing water Poor land preparation

ment for photoperiod-sensitive cultivars for drought-prone areas may not be a lot under the direct-seeding system. Early planting of photoperiod-insensitive cultivars would allow the crop to mature early to escape late-season drought. The use of photoperiod-insensitive genotypes provides an opportunity to develop high-yielding cultivars (Mackill et al 1996). Yield is thus likely to increase with the use of photoperiod-insensitive cultivars and transplanting.

Competitive ability against weeds

Weeds are a major problem for direct-seeded rice in rainfed lowlands where the opportunity to control water is limited. With rather limited resources available for buying herbicides, farmers need rice cultivars that can suppress weed growth. Weed control can be greatly assisted by rapid crop establishment, which would then allow the rice crop to compete successfully against weeds. On the other hand, poor establishment or missing hills, which are common in rainfed lowlands, allows weeds to grow rapidly. Competitiveness is associated with early vigor, and this is discussed in the next section.

Competitiveness against weeds may be measured by the ratio of yield or biomass under unweeded and weeded conditions. Large genotypic variation was found in competitiveness against weeds under both upland (Garrity et al 1992) and lowland (Fischer et al 1997) conditions. Competitive cultivars are able to reduce weed biomass compared with noncompetitive cultivars. In the experiments of Fischer et al (1997), in which 10–14 semidwarf cultivars were compared under competition with *Echinochloa colona* (L.), rice biomass was negatively correlated with weed biomass. Characters associated with rice competitiveness may be determined without weeds in some cases, such as rice plant height. This will make genotypic selection much simpler. However, this is not always the case. For example, characters such as leaf area and tillering need to be tested in association with weeds (Fischer et al 1997).

Several plant characters have been identified for strong competitiveness: tall plants, good tillering ability, and high leaf area index (LAI). In the study of Bastiaans et al (1997), the competitiveness of IR8 and Mahsuri was compared by growing them under monoculture and also with a mixture of purple rice. Mahsuri was found to be more competitive, and this was associated with its height relative to IR8 and greater relative leaf area growth rate. A computer simulation model of competition indicated that morphological characteristics such as high relative leaf area growth rate, relative height growth, and maximum plant height are important determinants of rice competitiveness (Bastiaans et al 1997). Although tall rice plants may be advantageous in competition against weeds in general, some semidwarfs are as competitive as tall plants (Fischer et al 1997). Since tall plants are often low-yielding and tend to lodge, shorter intermediate height (e.g., between tall traditional plants and semidwarf plants such as KDML105 and RD23, respectively, in Thailand) would be desirable.

A high LAI has been found to be a good character associated with competitiveness against weeds. Rapid tillering at the seedling stage will certainly contribute to rapid leaf area development. Among rice genotypes, canopies with a high LAI are associated with greater light interception (Fischer et al 1997) and this would be the primary reason for greater competitiveness. The high LAI achieved by a particular rice genotype may be the result of high crop growth rate, but it may also be due to good partitioning of assimilates to leaves. A key element for a high LAI during the early growth stages appears to be the leaf-area-to-leaf-dry-weight ratio or specific leaf area (SLA). This character appears to be particularly important during the early growth stages when the canopy is small and expanding (Dingkhun et al 1997, 1998). Mean SLA of the whole canopy usually decreases with time, but genotypic ranking is consistent. Also, genotypic evaluation of this character appears to be possible without any associated weeds. *Oryza glaberrima* genotypes were found to be competitive against weeds (Dingkhun et al 1997). Recently, the competitive character was incorporated into *O. sativa* elite lines. The canopy of the progeny developed rapidly and suppressed weeds during the early growth stages, but, unlike the *O. glaberrima* parent, the progeny did not have excessive vegetative growth later. This enabled them to develop a good grain sink and produce high yield.

Another character associated with competitiveness is the growth duration of rice genotypes. Dingkuhn et al (1999) found quick-maturing cultivars to be rather susceptible to weed competition under upland conditions. We also found a similar effect in rainfed lowland rice in Thailand (Fig. 1). Long-duration rice cultivars are often advantageous as they have more time to recover from weed competition that may have taken place during the early growth stages.

Some characters that make rice cultivars more competitive against weeds are not necessarily good characters for high yield. Thus, there may be a trade-off between competitiveness against weeds and high yield potential (Dingkuhn et al 1999). For

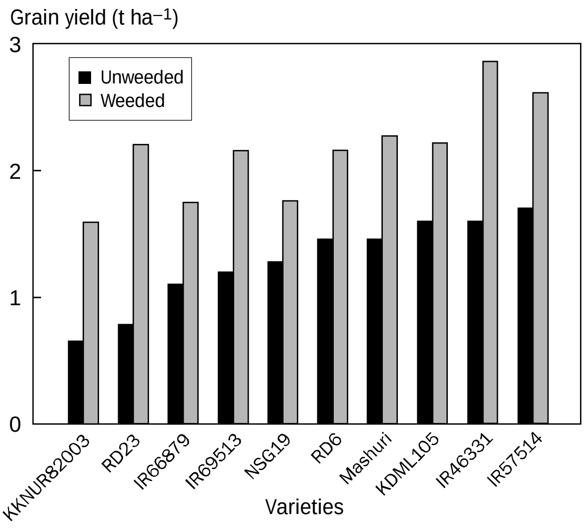

Fig. 1. Grain yield of 10 rice cultivars grown under broadcast and direct seeding with or without weed control, Khon Kaen, northeast Thailand.

example, cultivars with tall plants, a large number of tillers, or excessive vegetative growth may be competitive against weeds but may not be high-yielding under favorable conditions. Thus, the canopy type required depends on the quantity of weeds in the target environment. It is important to identify the conditions of the target environment before the type of cultivars required for direct seeding is determined.

Early vigor

High plant density. Good crop establishment is a key factor for the success of subsequent crop growth, and seedling rate and establishment percentage largely determine established plant density. High established plant density and even crop establishment in the field are required. Good seed quality is essential for this and seed storage conditions are important in determining seed quality. Seed size is also important in determining established plant density. For a given weight or volume of seeds that is sown in the field (e.g., 80 kg ha^{-1}), there are more seeds in small-seeded cultivars such as Mahsuri. Hence, they tend to have more plants per unit area. This is advantageous for subsequent crop growth. On the other hand, larger seeds are generally more vigorous and hence may have a higher percentage establishment, particularly under adverse conditions.

Seedling vigor. This is a particularly important genotypic character for rainfed lowlands where water control is limited. Seedling vigor is the plant's ability to emerge rapidly from the soil or water and cover the ground fast. It is often determined as shoot length at particular days after seeding (Redoña and Mackill 1996). Semidwarf cultivars have shorter mesocotyl and total seedling length and this is disadvantageous for good crop establishment, particularly when seeded deep in the soil or in standing water. Linkage between plant height at maturity and seedling length exists, but these are not pleiotropic characters (Dilday et al 1990). Therefore, it is possible to find semidwarf genotypes with tall seedlings at crop establishment (McKenzie et al 1994). High seedling vigor in rice is sometimes associated with some undesirable characters such as tall stature and large grain size, but in a study by Redoña and Mackill (1996) the association with plant height was not strong ($r < 0.53$). Threshold soil depth of seeding position at which 50% emergence was obtained varied from 3 to 8 cm depending on the cultivar. Generally, semidwarf cultivars have a small threshold depth.

Seedling vigor is a complicated trait that involves many loci and genotype by environment interaction is large (Mackill and Redoña 1997). In a study conducted by Redoña and Mackill (1996), the most vigorous cultivars were indica and temperate japonica types. However, further tests are required to confirm this; for example, tropical japonica lines developed at the Centro Internacional de Agricultura Tropical appear to have high seedling vigor.

Submergence tolerance. Rice can cope under submerged conditions either through rapid shoot elongation (shoot vigor) or tolerance of submergence. Cultivars with longer coleoptiles may be able to emerge from standing water, whereas other cultivars may die (Yamauchi 1995). Some cultivars are able to survive for a longer time than others under submerged conditions (Setter et al 1994) and this is a useful character where flash floods recede within several days. Although genotypes with submergence tolerance are often associated with poor agronomic characters and hence low yield, McKenzie et al (1994) were able to combine submergence tolerance and high yield. The genotype developed (IR49830-7-1-2-2) had intermediate height and is submergence-tolerant. The tolerance was not due to rapid shoot elongation (Mackill et al 1993).

Low-temperature tolerance. The use of deep water allows good weed suppression at crop establishment but the crop experiences lower temperature (McKenzie et al 1994). Low-temperature tolerance during crop establishment is important for irrigated dry-season crops in the tropics or for wet-season crops in temperate areas. Indica cultivars are not tolerant of low temperature compared with temperate japonica cultivars (Mackill and Redoña 1997). Tolerance for cold temperature was greatly increased by selecting semidwarf genotypes continuously under appropriate low-temperature environments.

Lodging resistance

Lodging is a common problem in rainfed lowland rice, particularly under direct seeding in highly fertile areas. Tall traditional cultivars tend to lodge and medium-tall cultivars are generally more suitable for direct seeding (Mackill et al 1996). According to Wang and Hoshikawa (1991), lodging occurs in the lower internode, which is not well overlapped by the leaf sheath. In taller cultivars, lower internodes tend to elongate and lodge. Mackill et al (1996) mention other characters that reduce lodging: large stem diameter, thick stem walls, and higher lignin content. Applying silicon increased stem rigidity, particularly under lower N fertilizer rates (Idris et al 1975). This helps reduce the occurrence of lodging. Lodging greatly destroys proper canopy structure. In a study by Setter et al (1997), in which lodging was induced during grain filling, the lodged canopy intercepted 80% of incident radiation in the top 5 cm compared with 80 cm in the unlodged canopy. This resulted in an 80% reduction in the rate of canopy photosynthesis in irrigated rice. The authors concluded that the adverse effects of lodging during grain filling were largely the result of self-shading by leaves and panicles.

In direct-seeded rice fields, root lodging is also common because seed position is rather shallow. Tolerant cultivars from the United States, which were bred under direct-seeding conditions, had heavier roots at heading, particularly at deeper depths compared with susceptible cultivars from Japan, which were bred under transplanting conditions (Terashima 1997). Mackill et al (1996) also mentioned that continued selection under transplanting may produce plants with shallow root systems.

Lodging may be avoided if seeds are sown deeper. In this case, cultivars with resistance to submergence would be advantageous (Yamauchi 1995).

Cultivar requirements for rainfed lowland rice

In addition to the specific requirements of cultivars for direct seeding, there are more general requirements for rainfed lowland rice cultivars. These are discussed more fully in Mackill et al (1996), Wade et al (1999), and Fukai and Cooper (1999). If the target rainfed lowland areas are favorable in general, then cultivar requirements would be

Table 3. Selection targets for improvement of grain yield of rainfed lowland rice within a maturity group against late-season drought using the Chum Phae drought-screening facilities in northeast Thailand.

Irrigated conditions
• High potential yield with
High harvest index
Intermediate height
• Low dry matter at anthesis
Rainfed conditions with drained water prior to anthesis
• Minimal delay in flowering
• Maintenance of favorable plant water status
Visual scoring for green leaf retention (drought score)
Reduced spikelet sterility

Source: Fukai and Cooper (1999).

similar to those for irrigated conditions, with emphasis on photoperiod-insensitive semidwarf cultivars with a high harvest index. On the other hand, if the environment is drought-prone, more drought-resistant cultivars are required. Fukai and Cooper (1999) suggest a selection method against late-season drought, which is common in many rainfed lowlands. The method is shown in Table 3.

One of the key requirements for rainfed lowland rice genotypes is that crop phenology match water availability. The water environment determines the crop phenological requirement. Fukai (1999) describes factors that determine the phenology in rainfed lowland rice. In some locations, particularly where the end of the rainy season occurs at the same time in different years, photoperiod sensitivity may be a desirable character. Another point is that semidwarf cultivars may not be suitable for areas where either flooding or drought will likely occur during the early growth stages. Nevertheless, cultivar height may be reduced from tall to more intermediate (Mackill et al 1996).

Appropriate rice breeding strategies for rainfed lowland rice would depend on how farmers in the target environment grow rice. If rice is established mostly from direct seeding, then the breeding program should use direct seeding. The breeding program may use both systems; for example, at the Central Rice Breeding Institute in Cuttack, India, breeding involves both transplanting and direct seeding in alternate generations. In other places, transplanting is used for early generation testing, whereas direct seeding is used for later generations (Singh and Dwivedi 1997). Continued selection under transplanting conditions is likely to produce plants that are prone to lodging and hence not suitable for direct seeding (Mackill and Redoña 1997).

Some characters can be selected under favorable conditions, such as large SLA. For characters such as this, the breeding system can be simplified. Early vigor may be selected rather easily as only seedling growth is required. Seedling length can be used as a selection criterion in early generations. Other desirable characters may be more difficult to incorporate into elite lines and cultivars.

We can conclude that cultivar requirements for direct-seeded rice in rainfed lowlands depends on the growth environment of the target area. It is therefore important to identify growing conditions of the target area carefully before ideal cultivar types are determined.

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Manipulation of seed and seedling vigor and their implications for the performance of wet-seeded rainfed lowland rice

H. Kyu, S.T. Amarante, A.A. Gomez, H.P. Samonte, R.P. Robles, and L.J. Wade

In rainfed lowland rice, the shortage of labor for transplanting and the need to increase cropping intensity have resulted in a greater adoption of wet seeding. But the shift to wet seeding may reduce the reliability of stand establishment and increase competition from weeds. For improved performance of wet-seeded rice, a reliable and vigorous crop stand is needed to obtain stable yield and suppress weed growth. A better understanding of variation in seed and seedling vigor and the implications for yield stability is needed, especially for rainfed systems. This paper examines seed vigor in four lines by considering variation caused by environment, cultivar, and seed lot in the germination cabinet. The implications of variation in seed and seedling vigor were then examined in the greenhouse and the field. Seedling vigor had potential benefits for subsequent growth that may be carried through to yield. But, with severe late stress, adverse consequences may accrue if inputs were used to compensate for poor early vigor. Results demonstrated that plants could compensate for poor early vigor under suitable conditions. Possessing inherent seedling vigor was an advantage under unpredictable rainfed situations, since attempts to compensate for low seedling vigor by N application may be detrimental if water stress occurred late in the season. Further research is needed to better understand the dynamics of compensatory responses and to determine whether selection of cultivars with greater seed and seedling vigor can harness the benefits of adding inputs under all conditions, without the risk of getting lower yields if subsequent conditions are less favorable.

In the rainfed lowlands, direct seeding of rice is replacing transplanting because of inadequate labor for transplanting and the need to increase cropping intensity (Fujisaka et al 1993). But the shift to wet seeding may make stand establishment less reliable and may significantly increase competition from weeds. The uncertainty of getting a vigorous crop stand is a major constraint to the improved performance of wet-seeded rice.

Seed vigor affects seedling establishment in all cereal crops, particularly in direct-seeded rice (Seshu et al 1988). Plants from low-vigor seeds showed delayed flowering, fewer panicles and filled grains, and lower grain yield than those from high-vigor seeds of the same variety (IRRI 1991). Likewise, low-vigor seeds were associated with delayed emergence, reduced seedling survival, poor plant distribution, and disability and reduced seedling vigor of individual plants in the stand, with adverse consequences for yield and yield stability of sunflower (Wade and Meinke 1994). A better understanding is needed of the components of variation in seed and seedling vigor under different environments and the implications for yield stability, especially for rainfed systems. Thus, these studies were done to manipulate seed and seedling vigor by cultivar, seed source, seed age, and nutrient and water management to determine their implications for the performance of wet-seeded rainfed lowland rice.

Experiments were conducted under controlled environmental conditions in a germination cabinet, greenhouse, and field at IRRI in 1998 (Kyu 2000). The objective of the germination cabinet experiment was to quantify seed vigor and the interactive effect of cultivar, seed source, seed age, and temperature on the germination and vigor index of rice. The greenhouse and field experiments were conducted to quantify the effect of manipulating seedling vigor by cultivar, seed age, and nitrogen fertilization at the seedling stage on dry matter production and grain yield of wet-seeded rice, with and without drought stress. Overall, the objectives were to quantify the capacity to compensate for poor early vigor and to determine whether greater early vigor would be advantageous when plants are exposed to water stress later in the season.

Materials and methods

Experiment 1. Germination cabinet

The experiment was conducted at IRRI's Genetic Resources Center in Los Baños, Philippines, using a Conviron CMP 3244 germination cabinet from Controlled Environments Limited. A split factorial design with three replications was used with four cultivars (IR20, IR72, PSBRc14, NSG19), two seed sources for each cultivar (IR20: large, small; IR72: wet season, dry season; PSBRc14: wet season, dry season; NSG19: 1996, 1997), and two seed ages (normal, accelerated aging) in each of four temperature regimes (15, 20, 25, 30 °C). Accelerated aging was imposed by exposing seeds to 43 °C for 6 d at 97% relative humidity (Delouche and Baskin 1973) during January-February 1998. Each temperature regime constituted a trial. For each treatment combination, 50 seeds were placed on Whatman #1 filter paper in a petri dish, and 7 mL of distilled water was added to start germination. The filter paper was maintained in a saturated condition throughout the experiment by adding water when necessary.

Seeds with a radicle growth of 2 mm or more were considered germinated. Each day, germinated seeds in each petri dish were counted and discarded until germination was completed. The density of seed samples was measured by floating a sample of 500 seeds for each treatment in a solution with a specific gravity of 1.20. For each sample, seeds that sank were recorded as having high density. The remaining seeds were categorized into small filled seeds and unfilled seeds. Data for each sampling were analyzed by analysis of variance, with temperature regime as the main effect tested against temperature/run error, and the remaining sources and their interactions tested against residual error. From the cumulative germination data, a seed vigor index was calculated as $SGI = \Sigma (S_i/i)$, where SGI was the speed of germination index and S_i was the number of normal seedlings germinated at day i (Seshu et al 1988).

Experiment 2. Greenhouse experiment

The greenhouse experiment was conducted at IRRI in a randomized complete block design with three replications. There were two water regimes (well-watered and water-stressed), four cultivars (IR20, IR72, PSBRc14, and NSG19), two seed ages (normal, aged), and four nutrient management treatments (nil, P only, P and N, and P with controlled-release N). P was applied as solophos at 40 kg P_2O_5 ha^{-1} and N as urea or meister (controlled-release) at 100 kg N ha^{-1}. Twenty kilograms of sieved, air-dried, and sterilized sandy loam soil was placed in a plastic sleeve inside each PVC pot with a 20-cm diam. and 55-cm height. The sides of the pot were covered with aluminum foil to minimize the increase in soil temperature. Ten pregerminated seeds per pot were surface sown. Standing water was maintained at 2–3-cm depth. At day 15, plants were thinned to one healthy seedling per pot and water was withheld from the drought treatments.

Emergence was noted daily until completed. Plant height was measured daily from the soil surface to the tip of the uppermost leaf. Dry weights were recorded at day 15 (using three thinned seedlings pot^{-1}) and day 40. Analysis of variance and means comparison were conducted using BSTAT (McLaren 1996).

Experiment 3. Field experiment

The field experiment was laid out at IRRI in a split-plot design with three replications, two water regimes (well-watered or with drought imposed from 75 d after sowing, DAS) as main plots, and two cultivars (IR72, PSBRc14), two nitrogen regimes (nil or 100 kg urea ha^{-1} in split applications at sowing and at day 45), and two seed ages (normal, accelerated aging) as subplots. The soil was a Maahas clay (Wopereis 1993). Basal dressings of P (40 kg ha^{-1} as solophos) and K (20 kg ha^{-1} as muriate of potash) were incorporated during puddling. Pregerminated seeds were surface-sown on 15 July 1998. Water depth was maintained at 2–3 cm for the duration of the experiment in the well-watered treatment and until 75 DAS in the drought treatment. Rain shelters were used to keep out the rain until harvest. No damage from pests or diseases was observed.

Coleoptile emergence was recorded daily in two 50 × 50-cm quadrats per plot. Plant height was measured daily from the soil surface to the tip of the tallest leaf for three plants per plot. At 21, 56, 70, and 92 d, weights of green leaves, dead leaves, stems, and panicles were recorded from a 50 × 50-cm quadrat in each plot. Samples were oven-dried at 70 °C for 72 h and dry weights were recorded. Spikelets and grains were counted on a 10-panicle subsample and spikelet fertility percentage was calculated. Grain yield was determined from two 1 × 1-m quadrats in each plot. The data were analyzed using analysis of variance, with water regimes as main plots and the remaining sources and interactions as subplots.

Results

Experiment 1. Germination cabinet

Cultivars and seed sources differed in seed dimension, 1,000-seed weight, and seed density (Table 1). Table 2 shows cumulative daily germination as affected by seed source, cultivar, and seed density. Seed source 1 (large IR20, wet-season IR72, wet-season PSBRc14, and 1997 seed of NSG19) germinated well. In source 2 (small IR20, dry-season IR72, dry-season PSBRC14, and 1996 seed of NSG19), maximum germination of NSG19 was substantially lower than that of PSBRc14, which in turn was much lower than that of IR20 and IR72. Maximum germination was comparable for all cultivars in source 1 and for IR20 and IR72 in source 2 (about 93%), but dropped to 50% and 25% for PSBRc14 and NSG19 from source 2. Lower maximum germination was associated with a longer lag and slower progress in germination. A two-step germination pattern was observed in IR20, IR72, and PSBRc14 for seeds from source 1, with high-density seeds germinating first.

Table 1. Seed density (%), seed dimensions (mm), and 1,000-seed weight (g) of four cultivars from two seed sources used in the seed and seedling vigor experiments, IRRI, 1998. Seeds of high density sank in a solution with a specific gravity of 1.20. The remaining filled seeds were considered to have low density. Depending on cultivar, contrasting seed sources were based on seed size (large, small), season (wet, dry), or year (1997, 1996).

Cultivar	Seed source	Seed density (%)			Seed dimensions (mm)		1,000-seed weight (g)
		High	Low	Unfilled	Length	Width	
IR20	Large	63.0	36.5	0.5	8.7	2.4	21.9
IR72	Wet	71.4	25.9	2.7	9.2	2.5	23.6
PSBRc14	Wet	45.6	50.4	4.0	9.4	2.3	23.0
NSG19	1997	82.2	14.2	3.6	10.5	2.4	28.3
IR20	Small	66.0	33.1	0.9	7.8	2.4	20.8
IR72	Dry	67.4	30.0	2.6	9.1	2.5	23.7
PSBRc14	Dry	59.0	35.4	5.6	9.3	2.3	22.4
NSG19	1996	54.4	43.1	2.5	10.6	2.5	23.0

Table 2. Effect of seed source, cultivar, and seed density on cumulative daily germination (%), LSD 7.5 (P = 0.05).

Cultivar	Seed source	Seed density	Time after sowing (d) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IR20	Large	66.0	3	25	49	73	74	74	90	97	98	99	99	99	99	99	99	99	99	99
IR72	Wet	71.4	0	13	24	37	57	65	69	71	75	81	85	88	90	91	91	91	91	91
PSBRc14	Wet	59.0	0	18	26	47	61	66	69	75	81	87	89	90	90	90	90	90	90	91
NSG19	1997	82.2	1	22	32	63	69	70	73	79	82	84	85	85	85	86	86	86	87	87
IR20	Small	63.0	1	24	39	68	73	73	86	94	97	97	97	97	97	98	98	98	98	98
IR72	Dry	67.4	0	4	22	29	46	60	65	68	70	74	79	83	86	89	90	90	91	91
PSBRc14	Dry	59.0	0	1	10	17	23	30	37	39	42	43	44	45	47	48	49	49	50	50
NSG19	1996	54.4	0	0	4	7	10	13	15	17	20	22	23	24	24	25	25	25	25	25

Table 3. Effect of seed source and cultivar on seed germination index (SGI) in four temperature regimes.

Cultivar	Seed source	Temperature (°C) 15	20	25	30
IR20	Large	6.67	13.84	14.85	27.26
IR72	Wet	4.25	8.43	10.45	19.71
PSBRc14	Wet	4.79	9.15	10.63	22.07
NSG19	1997	3.66	11.63	12.29	23.81
IR20	Small	6.35	12.48	13.77	25.03
IR72	Dry	3.71	7.01	9.63	16.84
PSBRc14	Dry	0.86	3.51	6.20	9.20
NSG19	1996	0.04	1.28	2.70	5.23
LSD (5%)		0.55	1.27	1.69	1.45

Table 3 shows seed germination index (SGI) as affected by seed source and cultivar in the four temperature regimes. SGI increased with temperature and was higher in IR20 than in other cultivars. For source 2, SGI was maintained in IR20 and to some extent in IR72, but dropped severely in PSBRc14 and NSG19, especially at low temperature.

Experiment 2. Greenhouse experiment

Emergence was completed at 6 DAS, with a higher maximum emergence percentage in IR20 and NSG19 than in IR72 and PSBRc14 (Table 4). Since emergence was completed by day 4 in IR20 and NSG19 and by day 5 in IR72 and PSBRc14, the range in percentage emergence declined from day 3 to day 6. Accelerated aging reduced emergence percentage, but the effect was greater in IR72 and PSBRc14, which germinated at a much slower rate because of aged seeds.

NSG19 was 15 cm taller than the other cultivars at 15 d (Table 5). At harvest (40 d), NSG19 was the tallest and IR20 the shortest. Accelerated aging reduced plant

Table 4. Seedling emergence (%) in seed from normal and accelerated-age batches of four rice cultivars.

Days after sowing	IR20		IR72		PSBRc14		NSG19		LSD (5%)
	Normal	Aged	Normal	Aged	Normal	Aged	Normal	Aged	
3	97.5	92.1	63.3	65.0	60.8	27.9	92.5	85.8	1.3
4	97.5	95.0	87.1	84.3	80.8	58.8	96.3	93.3	1.0
5	97.5	95.4	91.7	87.5	85.4	66.3	97.1	95.8	0.8
6	97.5	95.4	91.7	86.7	85.4	66.3	97.5	95.8	0.8

Table 5. Plant height (cm) development in four cultivars from normal and aged seeds.

Cultivar	Seed age	Time after sowing (d)									
		2	7	12	15	16	21	26	31	36	40
IR20	Normal	5	15	28	35	35	43	49	54	57	59
	Aged	4	15	27	34	35	44	50	55	57	59
IR72	Normal	2	14	29	36	38	47	54	61	65	68
	Aged	2	16	30	37	40	47	55	61	66	66
PSBRc14	Normal	1	13	28	36	38	47	55	61	65	67
	Aged	1	11	24	32	36	46	54	59	62	65
NSG19	Normal	5	24	42	50	53	65	79	86	88	90
	Aged	3	21	42	49	51	62	77	85	89	91
LSD (5%)		1	1	2	2	2	2	2	2	2	4

height significantly in PSBRc14 and NSG19 until about day 16. After day 20, however, PSBRc14 and NSG19 recovered, such that, at day 40, plant heights were similar across seed sources for all cultivars.

At day 15, seedling dry weight of NSG19 was double that of IR72 and PSBRc14; IR20 was intermediate (Table 6). Seed age did not affect seedling dry weight of IR20 and IR72, but aged seed reduced the dry weight of PSBRc14 and NSG19 significantly. By day 40, dry weights of cultivars were more similar than at day 15. With normal seed, NSG19 had a greater dry weight than IR72, which was heavier than PSBRc14 and IR20 (Table 7). With water stress, dry weights were halved, with NSG19 having a higher dry weight than IR20.

Experiment 3. Field experiment

The emergence percentage from days 10 to 17 showed an interaction between accelerated aging and N (Table 8), with a higher percentage observed when N was applied to normal seeds. Throughout the growing period, plants from normal seeds of PSBRc14 were taller than those from normal seeds of IR72 (Table 9). Plants from aged seeds of IR72 were taller than those from normal seeds. Accelerated aging reduced the height of PSBRc14 at tillering, but it recovered later.

If seedlings did not receive additional N, the dry weights of seedlings from normal and aged seeds were comparable (Table 10). Applying 100 kg N ha^{-1} signifi-

Table 6. Effect of seed age and cultivar on seedling dry weight (g) at 15 d after sowing. Interaction LSD 0.03 (P = 0.05).

Seed age	Cultivar			
	IR20	IR72	PSBRc14	NSG19
Normal	0.23	0.18	0.18	0.36
Aged	0.21	0.18	0.12	0.30

Table 7. Effect of cultivar and water regime on total dry weight (g) at 40 d after sowing. Interaction LSD 0.03 (P = 0.05).

Water regime	Cultivar			
	IR20	IR72	PSBRc14	NSG19
Well-watered	20.44	24.68	21.71	28.84
Water-stressed	9.63	10.50	10.36	11.53

Table 8. Effect of seed age and nitrogen on emergence (%), 10–17 d after sowing in the field.

Seed age	Nitrogen (kg ha^{-1})	Time after sowing (d)						
		10	11	12	13	14	16	17
Normal	0	29.0	34.2	38.6	46.3	51.9	60.5	68.2
	100	41.8	48.0	59.8	69.1	75.1	91.5	100.8
Aged	0	27.0	31.1	35.2	41.9	47.0	56.2	59.8
	100	27.2	31.5	36.4	42.2	48.0	57.5	63.3
LSD (5%)		7.0	6.9	8.6	10.6	11.2	13.2	14.4

Table 9. Effect of seed age and cultivar on plant height (cm), 34–74 d after sowing.

Growth stage	Days after sowing	IR72		PSBRc14		LSD (5%)
		Normal	Aged	Normal	Aged	
Tillering	34	46.8	49.6	52.1	49.3	2.7
PI[a]	44	58.6	61.1	64.5	63.4	3.2
Booting	54	67.9	72.2	73.8	70.5	4.1
Heading	64	74.7	80.9	87.3	85.2	4.4
Grain filling	74	91.5	95.5	104.0	110.5	5.5

[a]PI = panicle initiation.

cantly increased seedling dry weight in plants from normal seeds. By the panicle initiation stage, plants from aged seeds started compensating for the lower initial dry weight and response to applied N continued throughout the experiment (Table 11).

At a high N application rate, grain yields of both cultivars were similar under both water regimes (Table 12). With the use of aged seeds at high N, yields remained at

Table 10. Effect of seed age and nitrogen on seedling dry weight (g), 14 d after sowing. Interaction LSD 0.17 (P = 0.05).

Seed age	Nitrogen (kg ha^{-1})	
	0	100
Normal	1.55	2.19
Aged	1.65	1.97

Table 11. Effect of nitrogen on shoot dry weight (g m^{-2}) at 14, 56, 70, and 92 d after sowing.

Nitrogen (kg ha^{-1})	Days after sowing (d)			
	14	56	70	92
0	1.60	291.9	395.1	851.9
100	2.08	433.8	584.7	1194.8
LSD (5%)	0.17	21.5	28.1	53.9

Table 12. Effect of the interaction among water, cultivar, seed age, and nitrogen on grain yield (t ha^{-1}). Interaction LSD 0.51 (P = 0.05).

Seed age and nitrogen level (kg ha^{-1})	Well-watered		Water-stressed	
	IR72	PSBRc14	IR72	PSBRc14
Normal				
100	5.0	4.7	4.8	4.7
0	3.5	4.1	3.4	3.6
Aged				
100	4.6	4.9	5.0	4.3
0	3.5	3.5	3.4	3.9

about 4.8 t ha^{-1}, except for PSBRc14, which yielded 4.3 t ha^{-1} under water stress. At low N, yields of IR72 consistently decreased to about 3.4 t ha^{-1}. Overall, yields at high N averaged about 4.8 t ha^{-1} and averaged 3.5 t ha^{-1} at low N. But there were two exceptions for PSBRc14: at low N with normal seed in well-watered conditions and at high N with aged seed in water-stressed conditions.

Discussion

In the germination cabinet, variation in seed vigor as evidenced by SGI was mainly dominated by temperature, followed by variety and seed source, and, last, by accelerated aging. Seed source was important, especially in sensitive cultivars that were more affected by low-temperature conditions. The observed two-step germination pattern in some seed sources was related to the seed density fractions. Wade and Meinke (1994) observed that in sunflower the lower density fraction was slower to emerge and was less vigorous, making it more sensitive to unfavorable weather conditions following establishment.

In the greenhouse, aged seed of PSBRc14 and NSG19 initially had low height and dry weight, but caught up with the other plants later. Water stress reduced dry weight without changing the cultivar ranking. In the field, crop establishment and seedling vigor were influenced by cultivar, seed age, and N supply. N improved the survival of newly emerged seedlings, which encountered short-term flooding after emergence in this experiment. Some recovery for poor early vigor was possible with good seed under favorable conditions, as shown by improvement in plant height and dry weight in aged seeds, especially when N was applied.

Yields averaged 4.8 t ha^{-1} at high N and 3.5 t ha^{-1} at low N, with two exceptions for PSBRc14. With good seed, PSBRc14 was able to extract additional N and yield more than expected in the absence of applied N in well-watered conditions (i.e., with higher seedling vigor, yield increased from 3.5 to 4.2 t ha^{-1} at low N, LSD = 0.51, P = 0.05). With good seed, PSBRc14 was able to respond to applied N with late water stress, but, with aged seed, the response was delayed and yield was lower (i.e., with lower seedling vigor, yield decreased from 4.8 to 4.2 t ha^{-1} at high N with water stress, LSD = 0.51, P = 0.05).

PSBRc14 was better adapted to rainfed lowlands (Regmi 1995, Wade et al 1996), was more stable under unfavorable conditions, and was more sensitive to seed age and decline in seed quality. There is a need to use good-quality seed of PSBRc14, or backcross greater vigor to this adapted cultivar, using methods described by Mackill and Redoña (1997). Seedling vigor has potential benefits for subsequent growth that may be carried through to harvest. With severe late stress, adverse consequences may result if inputs are used to compensate for poor early vigor. Inherent seedling vigor is advantageous under unpredictable rainfed situations, since, as shown in this study, attempts to compensate for low vigor by N application may be detrimental if late water stress is encountered. Further research is needed to better understand the dynamics of compensatory responses and to determine whether selecting cultivars with greater vigor can harness the benefits of input addition under various conditions without risk if subsequent conditions are less favorable. Implications for weed suppression should also be addressed.

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The dry-seeding technique for saving water in irrigated rice production systems

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The dry-seeding technique, as an alternative to the transplanting method of rice crop establishment, was evaluated for its usefulness and farmers' adoption potentials for three consecutive wet seasons from 1995 to 1997 in the Upper Pampanga River Integrated Irrigation System (UPRIIS) service area, Philippines. The effects of two water regimes (continuous standing water and continuous saturated soil condition) and two methods of weed control (recommended herbicide weed control only and recommended herbicide plus hand weeding on dry-seeded rice) were evaluated in field experiments. The feasibility of dry seeding was also assessed by comparing its yield performance with yields of transplanted rice from neighboring farmers' fields.

Results showed that when weed growth was not a major problem, which was the case in the last two years, the average yield of dry-seeded rice was similar to that obtained in transplanted or wet-seeded rice on neighboring farms. In dry-seeded rice, yield from plots with continuous standing water was statistically the same as that from plots with continuous saturated soil water. But when weed growth was high, yield from the combined treatment of herbicide and hand weeding was significantly higher than that from the herbicide treatment alone.

The use of the dry-seeding technique eliminated the need for irrigation water during land preparation. Fields were plowed, harrowed, leveled, and seeded in dry or moist soil. This allowed rainfall to be more effectively used to support seed germination and crop growth than transplanted rice. About 32% and 22% of the total water used was from the irrigation source applied to supplement rainfall for maintaining continuous standing water and continuous saturated soil regimes, respectively, in the experimental field.

Most of the 21 randomly selected farmers who were interviewed in 1997 said that dry seeding was a good alternative to transplanting because rainfall and irrigation water were used more produc-

tively. They emphasized that the dry-seeding technique was appropriate, especially when irrigation water was scarce, because it was possible to prepare and broadcast seeds even in dry or moist soil conditions. A few farmers, however, were concerned that dry seeding may be difficult to adopt in areas with clayey soils because of tilling problems under dry conditions.

During the 1998 wet season, a serious water shortage was experienced in the UPRIIS service area. Three farmer-collaborators during the field experiment and one additional farmer adopted the dry-seeding technique and obtained yields of 3.0–3.7 t ha^{-1}. Moreover, the 17 neighboring farmers who similarly adopted dry seeding got average yields of 3.4–4.0 t ha^{-1}. About 50% of these farmers obtained significantly lower yields in the 1998 wet season than in the 1997 wet season. Despite the low yields in 1998, farmers who adopted dry seeding expressed satisfaction with the method because they were able to grow a rice crop despite the serious water shortage. They also did not need to spend money to control golden snails (a problem in transplanted rice) or to pay for extra labor for transplanting.

Transplanting is the dominant method of crop establishment in the irrigated rice systems of Asia (Yoong and Hui 1982, Mabbayad and Obordo 1970). Its major advantages are good weed control—it gives seedlings a headstart over aquatic weeds—and the relative ease of mechanical and manual weeding. But transplanting is labor-intensive and land preparation for transplanted rice, which is generally accomplished by soil puddling, consumes large amounts of water, about 20–40% of the total water required for growing the crop (Bhuiyan et al 1995). Soil puddling consists of three phases: land soaking to saturate, submerge, and soften the soil; plowing (once) to loosen, invert, and crush the soil; and harrowing (2–3 times) to puddle, level, and smooth the soil before the crop is transplanted. In large-scale irrigation systems, such as the Upper Pampanga River Integrated Irrigation System (UPRIIS), farmers usually flood the whole field with about 5–10-cm depth standing water before preparing their wet seedbed. While the field is being prepared, a shallow water depth is maintained continuously until seedlings are about 20–25 d old and ready for transplanting.

During transplanting, the field can be either drained to soil saturation or a shallow water depth can be maintained after the last harrowing and leveling operations. In the former (soil saturation), the field is reirrigated to a shallow water depth about 1 wk after transplanting In the latter, the depth of standing water is gradually increased to about 2–5 cm 1 wk after transplanting. This depth is maintained either continuously or by alternate wetting and drying until about 15 d before harvest when the field is drained to hasten crop maturity.

The increasing scarcity of water resources in irrigated rice systems and the competition from industrial, domestic, and nonrice agricultural sectors suggest the need to use and conserve rainfall and irrigation water more efficiently. To do this, ways must be found to reduce irrigation water use, increase the effective use of rainfall, and reduce labor costs in irrigated rice production systems.

Direct seeding is another rice establishment method that is relatively less labor-intensive. The field should be thoroughly prepared and leveled to ensure effective water control and maintain the uniform water depth that is required for good seed germination and uniform crop growth. The two methods of direct seeding are wet seeding and dry seeding. In wet seeding, pregerminated seeds are either drilled or broadcast onto wet, puddled, and leveled fields; in dry seeding, ungerminated seeds are either drilled or broadcast onto dry, nonpuddled, and leveled fields.

The dry-seeding method of rice establishment is not new. It is commonly practiced in the United States and Australia and is used to varying extents in other temperate countries (Mabbayad and Obordo 1970, Nazaki 1981, Akita 1992). Recently, the dry-seeding method has spread rapidly in the irrigated areas of Malaysia. This was reported to be due to the failure of irrigation systems to supply the amounts of water that were needed to continue the transplanting method (Yoong and Hui 1982, Morooka 1992) and to save labor, water, and other resources (Wah 1998). In the Philippines, dry seeding is practiced on rainfed farms to achieve effective rainfall use and increase cropping intensity and productivity (Denning 1985, Lantican et al 1993, 1999). Moreover, Lantican et al (1999) reported that the success of dry seeding in rainfed lowland rice production systems depends largely on the effectiveness of weed control, especially during the first months of crop growth, and on the precision of land leveling.

The practical feasibility of using the dry-seeding technique to increase cropping intensity, water-use efficiency, and productivity in irrigated rice areas has yet to be systematically explored. This paper presents the results of a study conducted to assess the feasibility and practical adoption potential of the dry-seeding technique by farmers as an alternative to transplanting in areas served by irrigation systems. The research had the following specific objectives:

- To establish the feasibility and management requirements of a dry-seeded rice production system within irrigated areas,
- To determine opportunities for saving irrigation water and using rainfall more effectively, and
- To identify the requirements for and assess farmers' views on the benefits and drawbacks of the dry-seeding rice system.

Site description

The study was conducted at a site near San Jose City (15°42′56″N, 120°57′54″E) within the UPRIIS service area. The UPRIIS is owned and operated by the National Irrigation Administration (NIA). It is a reservoir-backed multipurpose irrigation scheme with a command area of about 102,500 ha and it has an average cropping intensity of 145%. Average rice yield is 3.0 t ha^{-1} in the wet season and 4.3 t ha^{-1} in the dry season.

Soil physical and chemical properties

The upper 30 cm of soils in the experimental area has textures from silty clay loam to clay loam with a bulk density of about 1.23 g cm^{-3}. The moisture contents (by weight) are about 58% at saturation, 33% at 0.3 bar, and 13% at 15 bar. These soil properties were important considerations in managing the water needs of the rice crop during the early vegetative stage when the crop was under nonflooded rainfed conditions.

The average (Kjeldahl) N (0.09%), available P (7.70 mg kg^{-1}), exchangeable K [0.13 meq (100 g^{-1})], and organic carbon (0.90%) contents of the soil were very low compared with the average properties of a fertile wetland soil (Ponnamperuma 1981). Further, Singh and Bhardwaj (1973) reported that the efficiency of applied nitrogen, particularly in nonflooded upland rice fields, can be increased by applying nitrogen in smaller quantities but more frequently at the early stages when plants are not sufficiently grown up to use and assimilate the applied nitrogen. Therefore, in the design of on-farm experiments, the applied NPK and its management was a major consideration.

Climate, rainfall pattern, and water supply

The experimental area is relatively dry from November to April and wet for the rest of the year. The long-term (1966-94) average annual rainfall was 1,986 mm with confidence limits at the 0.05 level of 143 mm (Fig. 1A). Ninety-one percent of this total annual rainfall occurred during the wet months (May to October), which is generally adequate to support wet-season rice, with some supplemental irrigation applied as needed during periods of low rains. In the dry months, however, irrigation water from the Pantabangan reservoir must be supplied to ensure good crop growth. The mean releases of irrigation water every 10 days from the reservoir during 1990-94 were generally low, 1.55 million cubic meters (mcm) during the wet months, but they increased to a maximum of about 8.20 mcm during the driest months in the dry season (Fig. 1B).

Cropping schedule

The regular cropping schedule designed for the UPRIIS is shown in Figure 2C. The wet season (WS) is from July to November and the dry season (DS) is from December to April. This schedule has formally been adopted since 1976, but cropping intensity still remains at about 145%, mainly because many farms were not adequately irrigated in the dry season because of the low water supply, flooding problems during the wet season caused by high rainfall and inadequate drainage facilities, and other socioinstitutional problems in the management of the system.

An evaluation of the long-term (1964-94) rainfall pattern (Fig. 1), water supply (Fig. 3), wind speed, occurrences of tropical storms or typhoons (Fig. 2A and 2B), and other climatic parameters indicated that the most appropriate time for establishing dry-seeded rice in the wet season is June (Fig. 2D). With this schedule, the WS crop can be harvested in mid-September or early October and thereby avoid or minimize crop damage from typhoons, which are generally more intense starting in the second

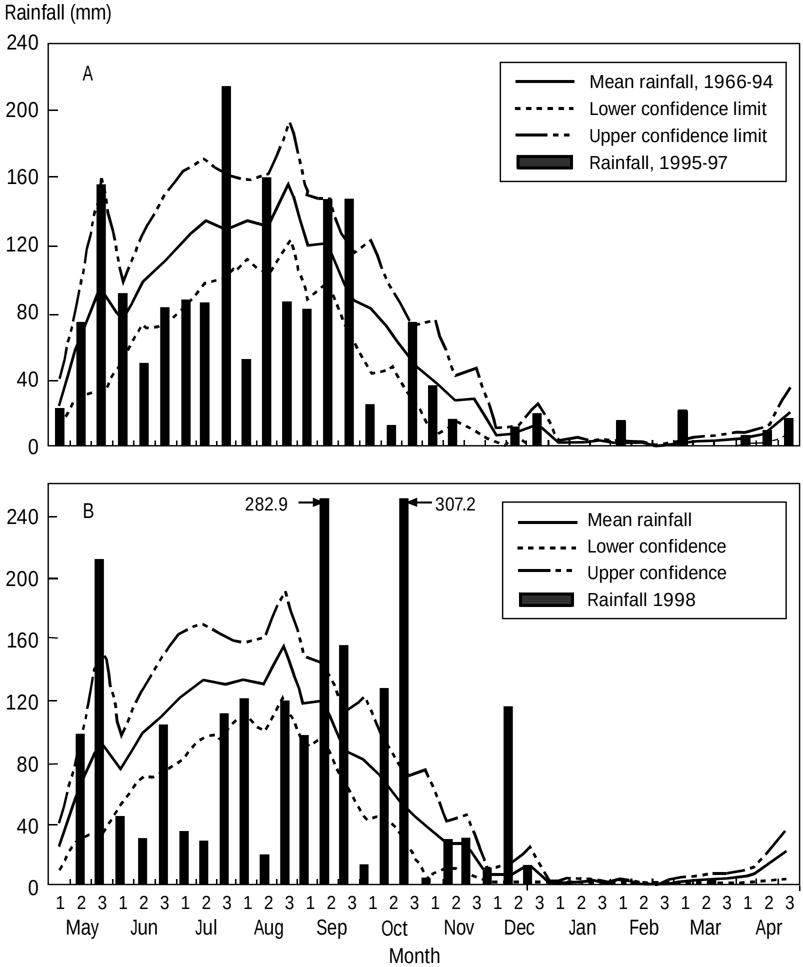

Fig. 1. Mean rainfall for every 10 days during the period 1966-94 compared with the (A) mean rainfall from 1995 to 1997 and (B) mean rainfall in 1998. PAGASA Station (15°44′N; 120°56′E), Central Luzon State University, Muñoz, Central Luzon, Philippines.

half of October. The dry-season crop could be established in either November or December depending on climatic and field conditions.

Materials and methods

This study was undertaken jointly by IRRI and the Philippine Rice Research Institute (PhilRice) in farmers' fields (15°42′56″N; 120°57′54″E) within the UPRIIS service area. It consisted of two components: field experimentation (1995-97) and farmer surveys (1997-98). An important aspect of the study was the assessment of the feasi-

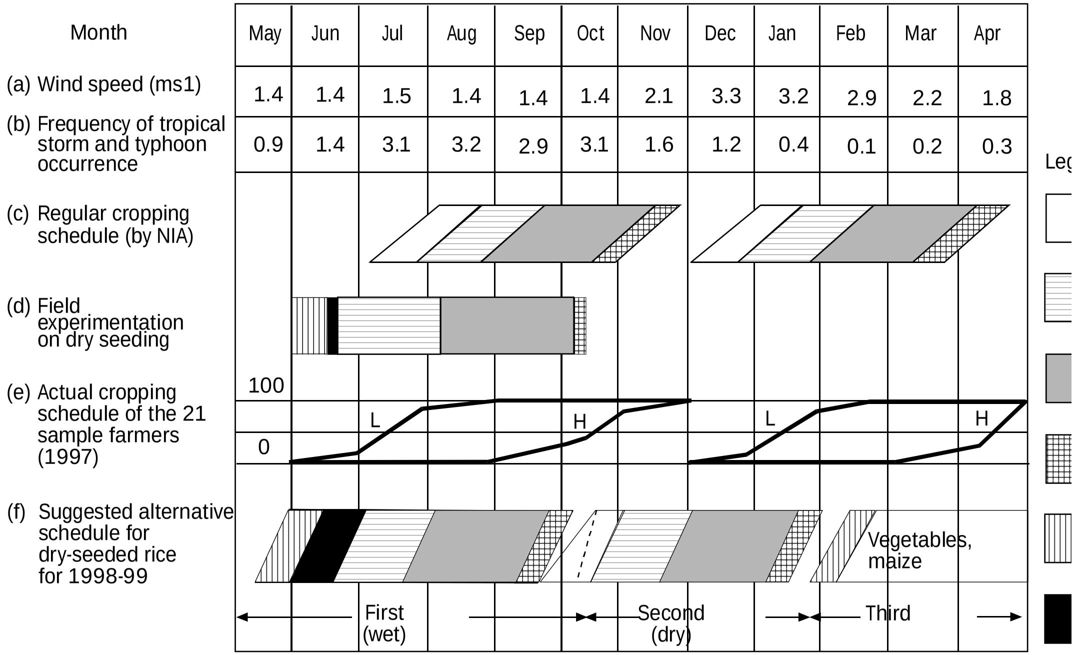

Fig. 2. Regular cropping schedule using transplanted and wet-seeded rice (c), field experimentation on dry-seeded rice (d), and suggested alternative schedule for establishment of dry-seeded rice in the 1998 wet season (e) in relation to climatic variables (a,b) within the Upper Pampanga River Integrated Irrigation System, Central Luzon, Philippines. (100% and 0% are the cumulative percentage of the sample farmers who adopted the cropping schedule.)

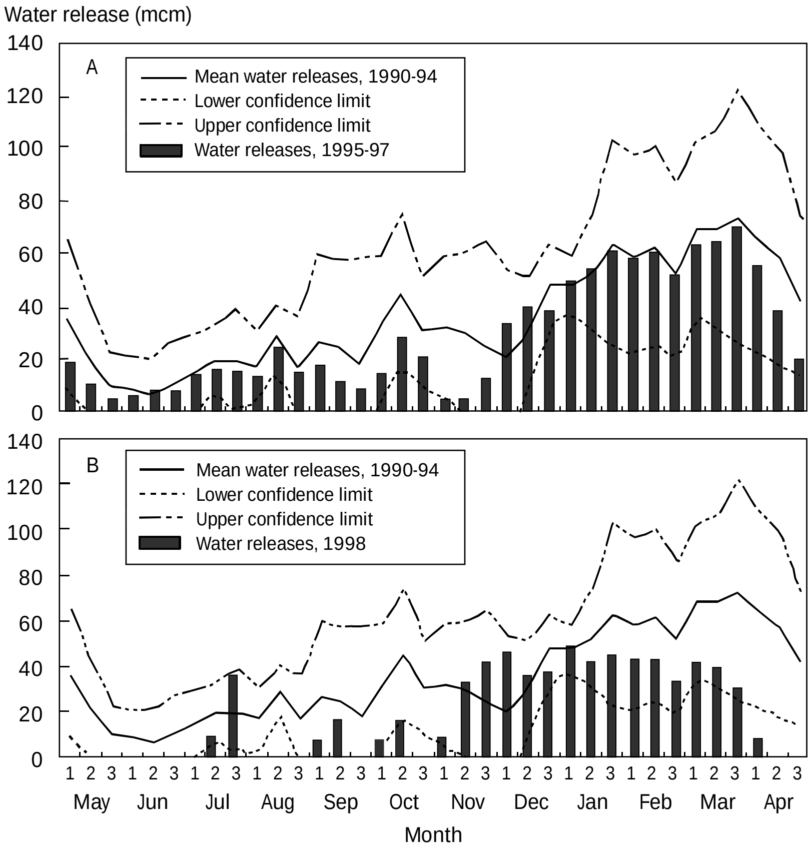

Fig. 3. Mean water releases for every 10 days from Pantabangan reservoir during 1990-94 compared with (A) mean water releases, 1995-97, and (B) mean water releases, 1998, Upper Pampanga River Integrated Irrigation System, Central Luzon, Philippines.

bility and practical applicability of adopting dry seeding by the NIA in its irrigation systems. In this regard, the operations manager and other concerned management and field staff of the NIA in Central Luzon, and from the central office in Quezon City, visited and assessed the field experiments on dry-seeded rice.

Experimental design (1995-97)

Four treatment combinations consisting of two water regimes and two weed control methods were evaluated for three consecutive wet seasons of 1995-97. The two water regimes, applied at about 15 d after seed emergence, consisted of continuous shallow (2–5 cm) standing water and continuous saturated soil. In the former, irrigation water was applied in plots to bring the water level to a 5-cm depth after it had been reduced to 2 cm. In the latter, irrigation was used to saturate the soil when the moisture content dropped to about field capacity.

The two weed control methods used were weed control using the recommended preemergence herbicide only and the application of recommended preemergence herbicide plus one hand weeding. The recommended herbicide was uniformly applied in all treatment combinations at recommended rates (0.075–0.500 kg ai ha^{-1}) within 5 d after seeding. Spot hand weeding (as required in the two treatments) was done within the first month of growth.

The four treatment combinations were shallow standing water (2–5-cm depth) plus weed control using recommended herbicide (TC1), TC1 plus one hand weeding (TC2), continuous saturated soil plus recommended herbicide weed control (TC3), and TC3 plus one hand weeding (TC4).

Treatment combinations were laid out in 12 × 8-m plots (average) in farmers' fields in a randomized complete block design. In 1995, the experiment was replicated twice on each of five selected farms. For more effective management and to increase the precision of the experiment, replications were increased to four on each of the three selected farms in 1996 and four on each of the two selected farms in 1997. The rice variety used was IR64, a cultivar preferred by farmers. The same farmer-collaborators were involved in any two consecutive years.

Fertilizer management

The required amounts of N fertilizer were applied in four splits: 10% at 10–13 d after emergence (DAE), 30% at 20 DAE, 40% at 50 DAE, and 20% at 60 DAE. In 1995, the amounts of N, P, and K fertilizers applied were 150 kg N ha^{-1}, 40 kg P ha^{-1}, and 40 kg K ha^{-1}. The following year, these rates were increased to 160, 90, and 90 kg ha^{-1} of N, P, and K, respectively. P and K fertilizers were all applied basally in all treatment combinations. In 1997, when weed growth was negligible, N rates were increased to 170 kg ha^{-1} for TC1, TC2, and TC3 and to 250 kg ha^{-1} for TC4. The required N was applied in four splits in TC1 and TC2, in three splits in TC3, and in five splits in TC4.

Insect and pest management

Proper field sanitation and sustained baiting for rodents were employed to minimize infestation and crop damage. Insecticides were used to control insects and pests and were applied at recommended rates, as required, within 41 days after sowing (DAS) during the 1995 and 1996 wet seasons. They were not necessary during the 1997 WS because many friendly insects (predators) were observed within the experimental area.

Field experimentation (1995-97)

Data gathered from the on-farm field experiment included water inputs (irrigation and rainfall) and yields. The climatic variables (i.e., wind speed, frequency of occurrence of tropical storm or typhoon) were obtained from the nearby station of the

Philippine Atmospheric Geophysical Services Administration (PAGASA) based at the Central Luzon State University (15°44′4″N; 120°56′07″E) at Muñoz, Nueva Ecija, Philippines.

Farmer survey (1997)

Twenty-one randomly selected farmers were interviewed using a structured questionnaire in the 1997 dry season to assess their perceptions regarding the benefits and drawbacks of dry seeding as an alternative to transplanting for water saving, for a more efficient use of rainfall and irrigation water, and to increase cropping intensity.

Data from farmer-volunteers who adopted dry seeding (1998)

During the 1998 WS, the water level at the Pantabangan reservoir was critically low, so the NIA management did not release any irrigation water for the early start of the wet season. Because of this and the scheduled upgrading of existing irrigation facilities, the NIA conducted a massive campaign among farmers to encourage them to adopt dry seeding and advance their cropping schedule 1 month earlier than usual (Fig. 2E). About 2,000 farmers (covering an area of 5,000 ha) adopted the technology (A. Mejia, NIA, personal communication). Among the adopters were four farmer-collaborators (same three farmers in 1996 plus one new farmer) who volunteered to evaluate the dry-seeding technique on their farm. Seventeen more farmers within the experimental area also adopted the technology, bringing the total area grown to dry-seeded rice in the 1998 wet season to about 25 ha.

Results and discussion

Rainfall pattern and water supply

The average annual rainfall in 1995-97 was 1,819 mm, of which 91% fell during the wet season, May to October. This amount was significantly less than the long-term (1966-94) average annual rainfall (1,986 mm) for the same period. In 1998, the total rainfall from June to the first 10 days of September was only 723 mm, which was only 60% of the long-term average total rainfall for the same period. The total rainfall in 1998, however, was higher (2,137 mm) than the long-term average and about 86% fell during the wet months (Fig. 1B).

The average water releases every 10 days from the Pantabangan reservoir during the periods 1990-94, 1995-97, and 1998 are shown in Figures 3A and 3B. In general, the average amount of water releases during the wet season was low but it increased during the dry season when rainfall was very low. During 1995-97, the average annual water release from the reservoir (1,050 mcm) was significantly lower than the average water release (1,289 mcm) during 1990-94. In 1998, the water release was only 686 mcm, of which only 94 mcm was released (47 DAS) to supplement rainfall during the wet season.

Field experimentation

In 1995, the average yield of dry-seeded rice across treatment combinations was 1.8 t ha^{-1} (Table 1). But the average yield of plots with weed control using both herbicides and hand weeding (2.4 t ha^{-1}) was significantly higher than the yield of plots with herbicide weed control only (1.3 t ha^{-1}). There was no significant difference in the average yield obtained from plots with either continuous standing water (TC1 and TC2) or continuous saturated soil water regime (TC3 and TC4). Compared with 1996 and 1997 (Tables 2 and 3), yields in 1995 were very low. This was due to a combination of severe weed infestation (average weed biomass density of 58 g m^{-2}), low water supply for almost 2 mo during the early vegetative growth period of the crop (Fig. 2), and the six tropical storms or typhoons (five of which occurred during the reproductive growth period) that damaged the crops.

The average seasonal water input (rainfall plus irrigation) was about 1,110 mm (Table 1). There was no significant difference in water inputs between the two water regimes as only 7–10% of the water input was from an irrigation source; the remaining came from rainfall. The average productivity of the irrigation water input (calculated as weight of rice produced over weight of water input) ranged from 1.5 to 3.5 g kg^{-1} in the continuous saturated soil and from 1.2 to 2.2 g kg^{-1} in the continuous standing water regime. Irrespective of water regime, the average irrigation water input productivity in plots where weed control was by herbicide plus hand weeding was about two times more than in plots that used herbicide only for weed control.

Table 1. Average yield, water input, and productivity of direct dry-seeded-cum-irrigated (IR64) rice, Upper Pampanga River Integrated Irrigation System, San Jose City, Central Luzon, Philippines, 1995 wet season.

Treatment combination[a]	Yield[b] (t ha^{-1})	Water input[b,c] (mm)	Water productivity[d] (g kg^{-1})	Irrigation productivity[e] (g kg^{-1})
TC1 (herbicide)	1.4 a (10.6%)	1,131.2 b	0.12	1.17
TC2 (herbicide + hand weeding)	2.3 b	1,118.4 a (9.3%)	0.21	2.23
TC3 (herbicide)	1.2 a (7.6%)	1,100.8 a	0.11	1.49
TC4 (herbicide + hand weeding)	2.4 b	1,088.3 a (6.4%)	0.22	3.49
Mean	1.9	1,109. 7	0.16	2.10
LSD	320.3	43.3		
CV (%)	23.0	3.47		

[a]TC1 & TC2 = continuous standing water (2–5-cm depth) starting at 15 days after emergence. The depth is gradually increased to 5 cm as the crop height increases. Water is drained 15 days before harvest; TC3 & TC4 = continuous saturated soil condition to field capacity. [b]In a column, means followed by a common letter are not significantly different at 0.05 level. [c]Water input is the sum of rainfall plus irrigation input. Values in parentheses are irrigation input expressed as percent of total water input. [d]Water productivity is the ratio of the mean yield to water input. It is expressed in grams per kg of water input. [e]Irrigation productivity is the ratio of the mean yield to the irrigation input. It is expressed in grams per kg of water.

Table 2. Average yield, water input, and productivity of dry-seeded-cum-irrigated (IR64) rice, Upper Pampanga River Integrated Irrigation System, San Jose City, Central Luzon, Philippines, 1996 wet season.

Treatment combination[a]	Yield[b] (t ha^{-1})	Water input[b,c] (mm)	Water productivity[d] (g kg^{-1})	Irrigation productivity[e] (g kg^{-1})
TC1 (herbicide)	4.3 a	1,403.9 a (38%)	0.31	0.80
TC2 (herbicide + hand weeding)	4.4 a	1,430.2 a (36.6%)	0.31	0.84
TC3 (herbicide)	4.1 a	1,340.8 a (32.7%)	0.31	0.94
TC4 (herbicide + hand weeding)	4.2 a	1318.1 a (31.7%)	0.32	1.00
Mean	4.3	1,389.7	0.31	0.90
LSD	944.4	209.0		
CV (%)	8.42	5.48		

[a]TC1 & TC2 = continuous standing water (2–5-cm depth) starting at 15 days after emergence. The depth is gradually increased to 5 cm as the crop height increases. Water is drained 15 days before harvest; TC3 & TC4 = continuous saturated soil condition to field capacity. [b]In a column, means followed by a common letter are not significantly different at 0.05 level. [c]Water input is the sum of rainfall plus irrigation input. Values in parentheses are irrigation input expressed as percent of total water input. [d]Water productivity is the ratio of the mean yield to water input. It is expressed in grams per kg of water input. [e]Irrigation productivity is the ratio of the mean yield to the irrigation input. It is expressed in grams per kg of water.

Table 3. Average yield, water input and productivity of dry-seeded-cum-irrigated (IR64) rice, Upper Pampanga River Integrated Irrigation System, San Jose City, Central Luzon, Philippines, 1997 wet season.

Treatment combination[a]	Yield[b] (t ha^{-1})	Water input[b,c] (mm)	Water productivity[d] (g kg^{-1})	Irrigation productivity[e] (g kg^{-1})
TC1 (herbicide)	4.7 a (50.2%)	1,976.4a	0.24	0.47
TC2 (herbicide + hand weeding)	4.7 a	1,863.4 ab (47.9%)	0.25	0.53
TC3 (herbicide)	4.4 a (28.5%)	1,279.2 a,b	0.35	1.21
TC4 (herbicide + hand weeding)	4.7 a	1,257.7 b (27.4%)	0.35 0.37	1.21 1.35
Mean	4.6	1,594.2	0.30	0.86
LSD	501.0	501.2		
CV (%)	6.35	16.08		

[a]TC1 & TC2 = continuous standing water (2–5-cm depth) starting at 15 days after emergence. The depth is gradually increased to 5 cm as the crop height increases. Water is drained 15 days before harvest; TC3 & TC4 = continuous saturated soil condition to field capacity. [b]In a column, means followed by a common letter are not significantly different at 0.05 level. [c]Water input is the sum of rainfall plus irrigation input. Values in parentheses are irrigation input expressed as percent of total water input. [d]Water productivity is the ratio of the mean yield to water input. It is expressed in grams per kg of water input. [e]Irrigation productivity is the ratio of the mean yield to the irrigation input. It is expressed in grams per kg of water.

In the 1996 WS, when weed growth was less than that of the 1995 WS, hand weeding did not significantly add to the yield as a result of applying herbicide (Table 2). Even so, the average yields from plots with continuous standing water (4.3 t ha^{-1}) and continuous saturated soil water regime (4.2 t ha^{-1}) were statistically the same. The mean yield for all treatments was 4.3 t ha^{-1}.

The water input was 1,324 mm in plots with continuous saturated soil and 1,417 mm in the continuous standing water regime (Table 2). The average amount of water input in different treatment combinations was statistically the same. About 37% and 32% of the total water amount were applied as irrigation to maintain continuous saturated soil and the continuous standing water regime, respectively. Irrigation water input productivity varied from 0.82 g kg^{-1} in the continuous standing water plots to 0.97 g kg^{-1} in the continuous saturated soil water regime.

In the 1997 WS, when weed growth was not a problem, the average yield was 4.6 t ha^{-1} and the water input (rainfall plus irrigation) was 1,594 mm (Table 3). There were no significant differences in yields obtained from plots in the different treatment combinations. Yield ranged from 4.4 t ha^{-1} in TC3 to 4.7 t ha^{-1} in TC2. The higher nitrogen rate (250 kg N ha^{-1}) applied in TC4 did not significantly contribute to increased yield compared with that obtained from the 170 kg N ha^{-1} used in other treatment combinations. The average 1997 WS yield obtained from neighboring farmers' fields was 4.1 t ha^{-1} on the five transplanted rice farms and 3.8 t ha^{-1} on the five wet-seeded rice farms. These indicate that, with good weed control and management, yields of dry-seeded rice are comparable with those obtained under traditional transplanting or wet-seeded rice fields.

The average water input (rainfall plus irrigation) in the continuous standing water regime was 1,920 mm and that for the continuous saturated soil was 1,268 mm (Table 3). The respective irrigation component was about 50% and about 30% of the total water input, respectively. The average irrigation water productivity was about 0.50 g kg^{-1} in the continuous standing water (TC1 and TC2) and about 1.28 g kg^{-1} in the continuous saturated soil (TC3 and TC4). This difference implies that a vast opportunity exists for increasing the effectiveness of irrigation water inputs in rice irrigation systems by maintaining a continuous saturated soil regime instead of the traditional continuous standing water in the paddy.

Feasibility and management requirements of the dry-seeded rice system

Crop scheduling. The dry-seeded experiment started with seeding from the first to the second week of June (Fig. 2D). The schedule was evaluated for three consecutive wet seasons in 1995-97. The crops were harvested in September or early October. This schedule provided an opportunity to maximize the use of rainfall, reduce the use of irrigation water, and minimize crop damage from tropical storms or typhoons.

The 1997 survey of 21 randomly selected farmers (with 6–50 years of rice-farming experience) within the experimental area revealed that 64% of the farmers established WS rice in July (Fig. 2E). About 14% and 21% established the rice by wet-seeding or transplanting methods in June and August, respectively. Correspondingly, most of the wet-season rice was harvested in October in accordance with the regular cropping schedule. In the dry season, 28% of the farmers established crops in December, 67% in January, and 5% in February. This schedule shows that most farmers do not establish the DS crop immediately after harvesting the WS crops. This is because they want to avoid the damaging effect of strong winds that generally occur from January to mid-February. The flowering stage of the rice crop would coincide with this strong-wind season, resulting in significant damage. Moreover, farmers need more time to transport and store their wet-season rice harvest. Farmers who established their dry-season rice crops beyond the regular schedule often request an extension of water releases from the reservoir to support their crops. This depletes the water in the reservoir, thus affecting the delivery of water in the next wet-season crop.

Farmers' perceptions of the feasibility of the dry-seeded rice system. Seventy-five percent of the 21 farmers interviewed in 1997 agreed that the dry-seeded rice system is a good alternative to traditional transplanted rice because it uses rainfall and irrigation water more effectively. In the dry-seeded rice system, it is possible to prepare the land without water and to broadcast dry seeds onto a dry (or moist) soil. They considered the system appropriate, especially for conditions when irrigation water is scarce. Fifteen percent of the farmers, however, were apprehensive about dry seeding, saying that weed problems could become serious and that yield may be lower than in transplanted rice. It was also mentioned that the method may be difficult to adopt in areas with clayey soils because of tillage problems.

Farmers' adoption of the dry-seeded rice system. The four farmer-collaborators (the same three farmers as in the 1996 wet season plus one) who adopted the dry-seeding method in the 1998 WS in June obtained yields of 3.0–3.7 t ha^{-1} (Table 4). Moreover, the 17 neighboring farmers who also adopted the technique obtained an average yield of 3.7 t ha^{-1} (Table 5). About 53% of the farmers obtained yields that were statistically the same as in the previous wet season. The remaining 47% obtained significantly lower yields (3.4 t ha^{-1}) in the 1998 WS than in the 1997 WS (5.3 t ha^{-1}). Despite lower yields in the 1998 WS, these farmers were still satisfied because

Table 4. Average yield (t ha^{-1}) obtained from direct dry-seeded rice[a] of four farmer-collaborators, Upper Pampanga River Integrated Irrigation System, Tondod, San Jose City, Central Luzon, Philippines, 1998 wet season, District I.

Farmer no.	Area (ha)	Yield (t ha^{-1})
1	3.00	3.7 ± 0.5
2	4.80	3.5 ± 0.6
3	0.12	3.0 ± 0.4
4	0.12	3.1 ± 0.2

[a]Crops were irrigated 44 days after sowing for a duration of 15 d. Values preceded by ± are the confidence limits at 0.05 level.

Table 5. Average yield (t ha^{-1}) obtained by two groups of farmers (high or low yields) who adopted dry-seeded rice (DSR) in the 1998 wet season (WS) compared with yields that they obtained from wet-seeded rice (WSR)/transplanted rice (TPR) in the 1997 WS, Upper Pampanga River Integrated Irrigation System, Tondod, San Jose City.

Farmer's group	Yield (t ha^{-1})		Difference[b]
	DSR (1998 WS)	WSR/TPR (1997 WS)	
I (high yield, 53%)[a] (n = 9)	4.0 a	4.2 a	–0.2 ns
II (low yield, 47%) (n = 8)	3.4 a	5.3 b	–1.9*
Total (100%) (n = 17)	3.7 a	4.7 b	–1.0*

[a]In a row, means followed by the same letter are not significantly different. [b]Differences marked with * are significantly different at 5% level, ns = not significantly different.

they were able to grow a WS rice crop at less cost for the control of golden (apple) snail and for transplanting labor. They also said that dry seeding was less tedious than transplanting. They further said that, if not for the serious water shortage, rat damage, and tropical storms or typhoons, which occurred between mid-September and mid-October (when their crops were at the maturity), they would have achieved the same or better yields than in the previous season. All in all, the farmers' responses to the dry-seeded rice system were positive. The difference in the supply of irrigation water between 1997 and 1998 had helped demonstrate to farmers some of the benefits of the dry-seeded system.

Conclusions and recommendations

The rainfall distribution in 1995-97 was similar to that of the long-term average (1966-94) or normal years, although the average annual rainfall (1,819 mm) was 167 mm lower. In 1998, the annual rainfall (2,137 mm) was higher than the long-term average, but the total rainfall during the crop growth period of the WS rice (1 June-10 September) was only 723 mm, which was only 60% of the long-term rainfall for the same period.

The average annual amount of water released (1,050 mcm) from the Pantabangan reservoir during the field experiments in 1995-97 was significantly lower than the water released (av. 1,289 mcm) during 1966-94. In 1998, the total water released was only 686 mcm, of which only 94 mcm was released from the 2nd 10 days of July (or 47 d after seeding) during the wet season.

The need for irrigation water during land preparation for crop establishment was eliminated with the use of the dry-seeding technique. Fields were plowed, harrowed, leveled, and seeded in dry or moist soil. In general, rainfall was effectively used to support seed germination and the early vegetative growth of the crop. Supplemental irrigation was applied only during the nonrainy days to support crop growth. Previous water management studies in the area had reported that water use for land preparation averaged 740 mm for wet-seeded rice and 895 mm for transplanted rice (IRRI 1993). These amounts are equivalent to about 40% of the total water used in wet-seeded or transplanted rice production systems. The potential amount of water that can be saved by shifting from puddled to nonpuddled land preparation and establishing the crop by the dry-seeding technique was quite high—between 7,400 and 8,950 $m^3\ ha^{-1}$.

The irrigation water input during the crop growth stage was low because rainfall was more effectively used and minimal amounts of irrigation water inputs were required to supplement rainfall. The average water use (rainfall plus irrigation) in the 1995-97 wet seasons was 1,478 mm for plots with continuous standing water and 1,275 mm for those with continuous saturated soil conditions. About 32% and 22% of these water inputs came from irrigation for maintaining the requirements for standing water and saturated soil moisture regimes, respectively.

In the 1995 WS, yields obtained from plots with weed control by both herbicide and hand weeding were significantly higher than those from plots that used herbicide only. In 1996 and 1997, when weed growth was less, the additional hand weeding did not increase yield. In all years, yields were statistically the same from plots with shallow standing water and from plots with saturated soil conditions. In 1998, yields on neighboring farms were 4.1 t ha^{-1} for transplanted rice and 3.8 t ha^{-1} for wet-seeded rice, which were both lower than the average of 4.6 t ha^{-1} obtained in the dry-seeded experiment.

The 21 randomly selected farmers who were interviewed after the 1997 WS said that the dry-seeding technique was a good alternative to transplanting because rainfall and irrigation water were used more productively. They emphasized that the dry-seeding technique was suitable, especially when irrigation water was scarce. Some farmers (15%), however, expressed a concern that weeds could become a serious problem and that yield could be lower, and about 5% of the farmers were apprehensive that it would be difficult to adopt the method in areas with clayey soils because of tilling problems under dry conditions.

During the 1998 WS, a serious water shortage was experienced in the UPRIIS service area. The four farmer-collaborators who adopted dry seeding obtained yields of 3.0–3.7 t ha^{-1}. The 17 farmers near the experimental area, who likewise adopted dry seeding, got average yields of 3.4–4.0 t ha^{-1}. About half of these farmers obtained lower yield in the 1998 WS than in the 1997 WS. Despite the lower yield, these farmers were satisfied because they were able to grow a decent rice crop with a very low irrigation water supply at less cost for transplanting labor and chemical control. They further said that if water shortage, rodents, and typhoon damage had not affected their 1998 WS crop, they would have obtained the same or better yields than in 1997.

Based on these findings, the following practices are recommended for dry-seeded rice:

1. Prepare and level the field thoroughly before drilling or sowing the seeds onto dry or moist soil to promote uniform seed germination and crop stand. Preemergence herbicide may be applied within 5 d after seed sowing. If weed growth becomes a problem after seed emergence, postemergence herbicide should be applied or spot hand weeding should be done within the first month of crop growth.
2. A 5-cm-high paddy spillway should be maintained to capture and store rainwater. Irrigation water, however, should be applied when soil moisture content is reduced to about field capacity but only to resaturate the soil. This will enable the soil to capture and store more rainwater in the field to satisfy the water requirement.
3. Other cultural practices such as fertilizer management and insect and pest control employed in transplanted or wet-seeded rice can also be adopted in dry-seeded rice, particularly when seeds have germinated and the soil is either saturated or flooded.

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Increasing water productivity in rice cultivation: impact of the large-scale adoption of direct seeding in the Muda irrigation system

R.J. Cabangon, T.P. Tuong, E.B. Tiak, and N. bin Abdullah

To ensure food security in Asia, it is imperative to identify rice production systems that require less irrigation water input than the conventional transplanted rice (TPR). This study investigated the effect of the large-scale adoption of wet-seeded rice (WSR) and dry-seeded rice (DSR) on irrigation input and water productivity based on kilograms of rice produced per unit volume of water input. Water balance components, crop establishment method, progress in farming activities, and rice yield of individual farmers were monitored in three irrigation service units (ISU) from 1988 to 1994 in the Muda Irrigation System of Malaysia. Yields did not differ statistically at the 5% level. Land preparation duration was significantly reduced in DSR and WSR compared with TPR. This led to a significant reduction in irrigation and total water input (rainfall and irrigation) during the land preparation period. However, TPR-ISU had a significantly shorter crop growth duration and lower irrigation and total water input than DSR-ISU and WSR-ISU. Over the whole crop season, water productivity of irrigation (WP_I) of DSR-ISU was significantly higher than WSR-ISU and TPR-ISU. Reduced irrigation input and higher WP_I in DSR-ISU were attributed to its ability to make use of early rainfall for early crop establishment. WSR-ISU had lower irrigation water than TPR-ISU because the water savings during the land preparation period outweighed the higher water input during the crop growth period. Since this may not be true in other conditions, site-specific management of WSR versus TPR has to be considered when assessing the relative advantage in water productivity.

Rice is the staple food of about half of the world's population. Global rice demand is projected to increase markedly by 2020. Much of this increase must come from the irrigated rice systems. Rice cultivation is known to be less water-efficient than the production of other food crops. Irrigated agriculture accounts for 90% of the total diverted fresh water in Asia, and about 50% of this is used to irrigate rice, while water is becoming increasingly scarce because of competition with nonagricultural uses. To ensure food security, it is essential to reduce the amount of water input in rice cultivation.

Conventionally, rice is established by transplanting. This involves growing seedlings in a nursery bed, with the seedbed in a separate section of the farm or as a part of the main field where rice will be grown. Seedlings are transplanted in main fields several weeks after sowing. Farming activities in the main field begin with presaturation irrigation to saturate the surface soil and to create a ponding water layer (about 5-cm depth) for soaking. This is followed by plowing and harrowing under saturated soil conditions (puddling operations). In the last few decades, because of the labor shortage and high labor cost for transplanting, there has been a shift to wet seeding. Wet seeding consists of sowing pregerminated seeds (soaked and incubated for 24 h each) directly onto puddled fields, which have been prepared in a similar way as for transplanted rice. When irrigation water is lacking at the beginning of the rainy season, farmers in some irrigation systems also practice dry seeding, that is, direct broadcasting of dry seeds onto dry or moist soil. Seeds germinate when there is enough rainfall to moisten the soil (Tuong 1999). An example of the rapid switch from transplanting to direct seeding (either wet seeding or dry seeding) is reported by Ho Nai Kin (1996) for the Muda Irrigation System in Malaysia. Prior to 1977, rice in the area was predominantly transplanted, but, in the mid-1990s, more than 95% of the area was direct-seeded.

Many researchers (e.g., My et al 1995) reported that dry seeding, compared with transplanting, led to advances in crop establishment, made better use of early season rainfall, and facilitated an increase in cropping intensification. The effect of dry seeding on water use and water productivity (amount of rice grain per unit of water input) in irrigated systems has not been reported. It is expected that, since land is prepared dry, the amount of water input for land preparation of dry-seeded rice (DSR) would be less than that for wet-seeded (WSR) and transplanted rice (TPR). Dry land preparation, however, means that puddling will not be able to reduce percolation in the soil. Increased water input because of higher percolation may outweigh water savings during land preparation. In the Philippines, Bhuiyan et al (1995) reported that WSR reduced irrigation water input because of the shorter land preparation period in WSR than in TPR. In the TPR system, farmers often delay land preparation, waiting for seedlings being nurtured in seedbeds. In the WSR system, land preparation is not hindered by raising seedlings. Findings by Bhuiyan et al (1995) may be specific to this study site, where individual farmers raised seedlings in their main fields; thus, seedbeds were scattered all over the site.

Most previous studies on water use in DSR and WSR were conducted in experimental plots or in small farmers' fields. At the block level in the Muda Irrigation System, Fujii and Cho (1996) found that the amount of irrigation water decreased significantly because of direct seeding. The authors did not distinguish between DSR and WSR, however, and their effect on water could not be compared. Furthermore, previous authors did not analyze the effect of crop establishment systems on different water balance components. Without these detailed analyses, it is not possible to explain differences in water inputs caused by crop establishment methods, and conclusions derived may be site-specific.

The objective of this study is to determine and compare components of water balance, water-use efficiency, and water productivity of DSR, WSR, and TPR grown on a large scale within an irrigation system.

Methodology

Study site

The study was conducted in three irrigation service units (ISU), A1, C4C5, and F5F6, in district III of the Muda Irrigation System. The system supplies water to 96,000 ha of paddy fields on the coastal plain of the states of Kedah and Perlis in Malaysia. The region has two distinct seasons—the dry season from December to March and the wet season from April to November, which accounts for about 85% of the annual rainfall of 2,100 mm (Ho Nai Kin 1996). The soil belongs to the Kuala Kedah soil series and is classified as a sulfaquent (Paramananthan 1978). It has a clay content exceeding 60% (Ho Nai Kin 1996).

There are two rice crops in the study area. The first crop, referred to as the wet-season crop, starts at the beginning of the rainy season. Farmers wait for the release of water from the reservoir, often in March, to apply presaturation irrigation. In some years, however, water release was delayed until April because of low water storage in the reservoir. The second season or the dry-season crop begins in August to September and ends in January to March of the following year. Before 1988, farmers practiced transplanting in both seasons. Since 1988, there has been a gradual switch from transplanting to direct seeding. After 1994, most farmers practiced direct seeding. Although both wet seeding and dry seeding are practiced in the rainy-season crop, farmers practice only wet seeding in the dry-season crop. Since the crop establishment stage of the second rice crop is in the middle of the rainy season, the soil is generally too wet for dry seeding. To compare dry seeding, wet seeding, and transplanting, only the first cropping seasons were considered in this paper.

Selected ISUs had areas of 30 ha (A1), 50 ha (F5F6), and 54 ha (C4C5). We carried out our study from 1988 to 1994 when the change from transplanting to direct seeding was actively taking place. In one year, farmers within one ISU practiced different methods of crop establishment: dry seeding, wet seeding, and transplanting. Table 1 shows the percentage of area of each ISU planted using different crop establishment methods during the study period. Each ISU year was then classified according to the crop establishment method that the majority of farmers in that ISU practiced in the specified year. Thus, an ISU year was classified as wet-seeded ISU (WSR-ISU) when more than 50% of the area practiced wet seeding. In Table 1, five ISU years were classified as DSR-ISU, four as TPR-ISU, and four as WSR-ISU.

Table 1. Percentage of area planted to dry-seeded rice (DSR), wet-seeded rice (WSR), and transplanted rice (TPR) in irrigation service units (ISU) A1, C4C5, and F5F6 and their classification according to the predominant crop establishment method in the ISU.

ISU	Year	% of ISU area			Classification
		DSR	WSR	TPR	
A1	1988	0	18	82	TP-ISU
(30 ha)	1989	0	38	62	TP-ISU
	1990	0	40	60	TP-ISU
	1991	84	10	6	DS-ISU
	1992	97	1	2	DS-ISU
	1993	66	17	17	DS-ISU
	1994	1	79	20	WS-ISU
C4C5	1988	2	90	8	WS-ISU
(54 ha)	1990	0	88	12	WS-ISU
	1993	42	57	1	WS-ISU
F5F6	1988	63	29	8	DS-ISU
(50 ha)	1990	2	26	72	TP-ISU
	1993	92	8	0	DS-ISU

Duration and progress of farming activities and grain yield

We monitored the dates of presaturation irrigation, land preparation, seeding or transplanting, and harvesting for each field. From this data, we computed the cumulative area (and expressed it in percentage of area of the ISU) that farmers covered for each farming activity. For each ISU year, we defined land preparation period as the time when 80% of the farmers completed presaturation until 80% of the farmers completed seeding/transplanting. Similarly, the crop growth period was from 80% seeding/planting to 80% harvest.

Grain yield of farmers was obtained from the rice-sales record book of the National Padi Board, supplied by the Muda Agricultural Development Authority (MADA). In each ISU, mean grain yields were computed for each crop establishment method.

Monitoring of irrigation and surface water and groundwater depth

Irrigation discharge in each ISU was monitored twice a day using constant head orifices installed at each entry point of the ISU. During irrigation, the discharge was kept constant, ranging from 40 to 70 L s^{-1}.

Field water depth was monitored daily with gauges installed at 10 locations within each ISU. Groundwater depth was measured daily in tubewells located next to the gauges. Daily rainfall (R) and class-A pan evaporation (Epan) were obtained from a weather station near the study area.

Water balance components

We computed the water balance for each year and each ISU for land preparation and crop growth periods.

Water balance components, expressed in millimeters of water over the ISU, can be expressed by equation 1

$$I + R = \Delta Ss + \Delta Sgw + (ET + E) + S\&P + D \quad (1)$$

where I = irrigation water input, R = rainfall, ΔSs = change in surface water storage, ΔSgw = change in groundwater storage, ET = evapotranspiration from rice area, E = evaporation from nonrice area, S&P= seepage and percolation, and D = surface drainage. The distinction between E and ET was necessary because farmers established and harvested the crop at different times. At any time, a part of the ISU might be covered with rice and another part not covered with rice.

Irrigation amount was derived from discharge measurements, ΔSs from the change in surface water depth, and R from weather station readings.

Computing E and ET. The value of E depended on whether the soil was saturated (e.g., after land soaking of WSR and TPR) or not (e.g., during dry land preparation for DSR). We assumed that evaporation from the saturated soil was equivalent to the class-A pan evaporation. Thus, evaporation from saturated soil, E_{sat}, over an ISU surface is

$$E_{sat} = (A_{nr\ sat}/A_{ISU}) \times Epan \quad (2)$$

where A = field surface area and subscripts nr = nonrice and sat = saturated.

Evaporation from unsaturated soil without rice (E_{unsat}) depended on the soil moisture condition:

$$E_{unsat} = (A_{nr\ unsat}/A_{ISU}) \times f \times Epan \quad (3)$$

where f = the factor that takes into account the effect of unsaturated soil conditions on evaporation; f varied linearly from 0.2 at the beginning of the season (i.e., cumulative rainfall = 0) to 1.0 when the soil became saturated. From rainfall and groundwater depths, we noted that the soil became fully saturated (i.e., when groundwater reached the soil surface) when the seasonal cumulative rainfall (starting from 1 March) was 350 mm. Thus, f = 1 at 350-mm cumulative rainfall.

From equations 2 and 3,

$$E = E_{sat} + E_{unsat} \quad (4)$$

For WSR and TPR, the soil was always saturated after crop establishment. For DSR, the soil became saturated when rainfall (or irrigation water) was adequate to bring the groundwater to the soil surface. The evapotranspiration from the saturated area with the rice crop, ET_{sat}, can be written as

$$ET_{sat} = (A_{r\,sat}/A_{ISU}) \times k_c \times Epan \qquad (5)$$

where subscript r denotes “with rice” and k_c is the crop factor, taken from Lembaga Kemajuan Pertanian Muda (1986).

For DSR, the soil may not be fully saturated right after sowing. Similar to the calculation of E, we adjusted the values of ET to take into account the effect of nonsaturated soils as follows:

$$ET_{unsat} = (A_{r\,unsat}/A_{ISU}) \times f \times k_c \times Epan \qquad (6)$$

The values of the coefficient f are similar to those in equation 3. The total ET from the cropped area is thus

$$ET = ET_{sat} + ET_{unsat} \qquad (7)$$

Computing S&P. The seepage and percolation rate was computed from daily observations of surface water depth during days (a) with no rainfall, (b) after the whole ISU was flooded, and (c) when farmers did not irrigate or drain the fields. During these days, S&P was calculated as

$$S\&P = DSs - ET \qquad (8)$$

An average value of the S&P rate for the season was then used to calculate S&P for days with standing water. For days without standing water, it was assumed that there was no S&P.

Computing ΔSgw. DSgw was estimated from the water table depth by equation 9, which was derived by Lembaga Kemajuan Pertanian Muda (1986):

$$DSgw = 8.263 \times (WD_f^{0.5} - WD_i^{0.5}) \qquad (9)$$

where WD_i = initial water table depth (cm) at the beginning and WD_f = final water table depth at the end of the computation period (in cm). $WD_i = 0$ and $WD_f = 0$ if the water table was above the soil surface.

Computing D. The amount of drainage was the closure term in equation 1, being the difference between all inputs (I + R) and all outputs (E + ET, S&P, ΔSs, and ΔSgw).

Water productivity

Water productivity (WP) is defined as production (grain yield) per unit volume of water. It can be measured in relation to irrigation amount (WP_I), total inflow (WP_{I+R}), depleted water (WP_{ET+E}), or process-depleted water (WP_{ET}) as follows (Molden 1997):

$$WP_I = Y/I \qquad (10)$$

$$WP_{I+R} = Y/(I + R) \quad (11)$$

$$WP_{ET+E} = Y/(ET + E) \quad (12)$$

$$WP_{ET} = Y/E \quad (13)$$

In these equations, Y is in kg ha^{-1} and all water components are in m^3 ha^{-1}.

Results and discussion

Progress of farming activities

Figure 1 compares the progress of farming activities in three ISUs using different crop establishment methods. Land preparation in WSR-ISU and DSR-ISU was completed about 10 d ahead of that in TPR-ISU. Similarly, the crop was established on 80% of the area of DSR-ISU and WSR-ISU on 3 and 4 April, about 1 mo ahead of the TPR-ISU (2 May). Harvest of 80% of the area of DSR-ISU was completed 1 wk earlier than WSR-ISU, which, in turn, was 2 wk earlier than TPR-ISU.

Table 2 summarizes the mean duration of farming activities in all ISUs as classified by crop establishment method. The land preparation period in DSR-ISU was about 24 d shorter than in WSR-ISU and in WSR-ISU it was 25 d shorter than in TPR-ISU. Crop growth period in TPR-ISU was 12 d shorter than in DSR-ISU and WSR-ISU. Over the whole season, the irrigation period of TPR-ISU was 12 d longer than that of WSR-ISU and that of WSR-ISU was 23 d longer than that of DSR-ISU (137 $\pm$ 5.5 d). Fujii and Cho (1996) also reported that the irrigation period of DSR was shorter by about 1 mo compared with WSR and by 2 wk compared with TPR.

Water balance components

Irrigation and rainfall. Figure 2 shows the water inputs during land preparation, crop growth period, and the whole crop season for DSR-, WSR-, and TPR-ISU. During land preparation, total water input in TPR-ISU was more than double that of WSR-ISU and almost three times that of DSR-ISU (Fig. 2A). Between the two direct-seeding methods, DSR-ISU reduced irrigation input by half compared with WSR-ISU. The rainfall in DSR-ISU, however, was slightly higher than in WSR-ISU. Rainfall in direct-seeding methods is much lower than in transplanting. There was no significant difference between total water input during land preparation in DSR- and WSR-ISU. Previous researchers (e.g., Bhuiyan et al 1995, Thabonithy and Murali 1994, IRRI 1999) reported that direct-seeded rice reduced the water input in experimental plots during land preparation compared with TPR. Our findings confirmed this for the ISU level.

During the crop growth period (Fig. 2B), irrigation water was lowest in DSR-ISU compared with WSR-ISU and TPR-ISU. The amount of rainfall in DSR-ISU, however, was significantly higher than in WSR-ISU and was significantly higher in WSR-ISU than in TPR-ISU. When both irrigation and rainfall were taken into account, the crop growth period of TPR-ISU had a significantly lower total water input compared with

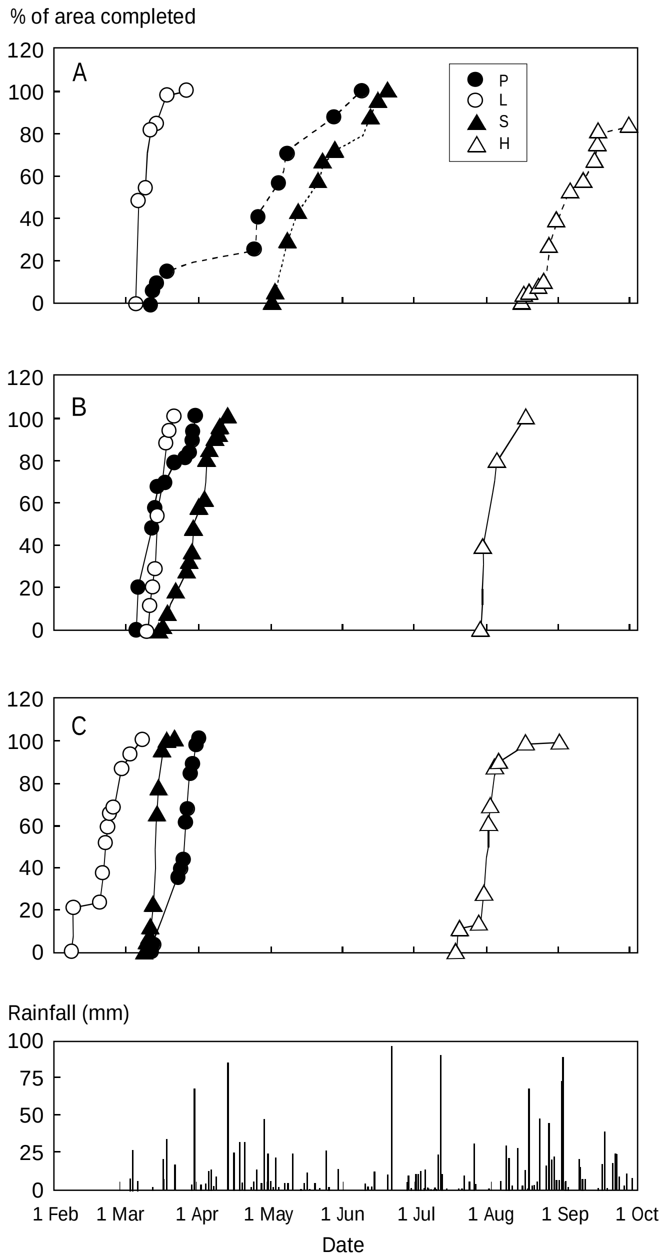

Fig. 1. Progress of farming activities in (A) irrigation service unit (ISU) A1 (transplanting), (B) ISU C4C5 (wet seeding), and (C) ISU F5F6 (dry seeding), Muda Irrigation System, 1988. P = presaturation, L = land preparation, S = seeding/transplanting, H = harvesting.

Table 2. Means ± standard error of farming periods in different irrigation service units (ISU) classified according to the predominant crop establishment method, Muda Agricultural Development Authority, 1988–94.

Period	DSR-ISU (N = 5)	WSR-ISU (N = 4)	TPR-ISU (N = 4)
Land preparation period[a] (d)	12 ± 7	36 ± 8	61 ± 2
Crop growth period[b] (d)	125 ± 7	124 ± 3	112 ± 2
Total (d)	137 ± 7	160 ± 6	172 ± 5

[a]From 80% completion of presaturation irrigation to 80% completion of seeding/planting. [b]From 80% completion of seeding/planting to 80% completion of harvest.

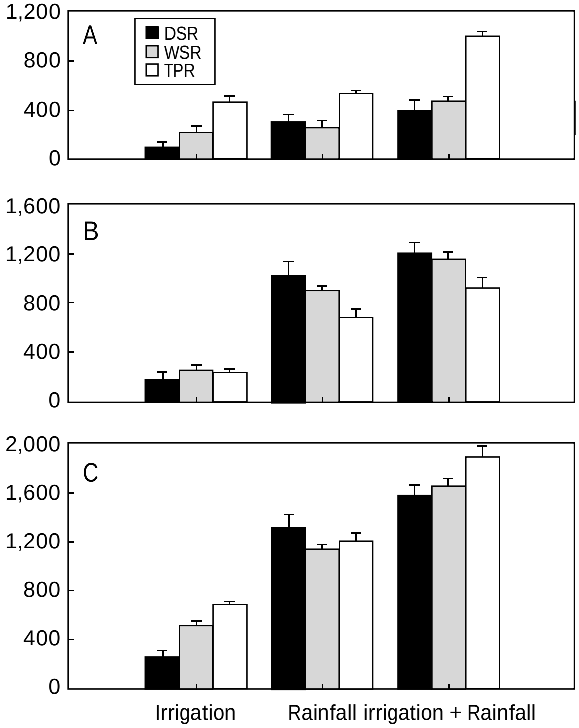

Fig. 2. Irrigation, rainfall, and total water input during the (A) land preparation period, (B) crop growth period, and (C) whole crop season in irrigation service units established by dry-seeded rice (DSR), wet-seeded rice (WSR), and transplanted rice (TPR), 1988-94, Muda Irrigation System, Malaysia.

WSR-ISU and DSR-ISU. The low irrigation water of DSR-ISU during the crop growth period was attributed to the ability of DSR to make use of rainfall, since seeds were sown before the arrival of presaturation irrigation. This also accounted for the higher amount of rainfall received by DSR-ISU than by WSR- and TPR-ISU. The lowest total water input during the crop growth period in TPR-ISU was attributed to its shorter crop growth period in main fields compared with WSR- and DSR-ISU (Table 2).

Irrigation water over the whole season (Fig. 2C) in DSR-ISU was about 200 mm less than in WSR-ISU and was 220 mm less in WSR-ISU than in TPR-ISU. Rainfall was higher in DSR-ISU than in WSR- and TPR-ISU. Total water input was highest in TPR-ISU. There was no significant difference in total water input between DSR-ISU and WSR-ISU. The increase in water input in TPR-ISU came from the increased supply during the land preparation period.

Evaporation and evapotranspiration

Figure 3 shows that the evaporation from the nonrice area in TPR-ISU was about 140–170 mm higher than in WSR-ISU and DSR-ISU. This was consistent with the longer duration of land preparation periods during TPR- and WSR-ISU (Table 2). ET did not differ significantly among the three crop establishment methods. Temporal variations in ET have masked the effect of shorter (by about 10 d) crop growth duration in TPR-ISU compared with that of WSR- and DSR-ISU (Table 2). Over the whole crop season, atmospheric depletion (E + ET) was highest in TPR-ISU, followed by WSR- and DSR-ISU. Differences among the different crop establishment methods came from the difference in E from nonrice areas.

Seepage and percolation

The S&P rate, ranging from 1 to 4 mm d^{-1}, with an average of 2.5 mm d^{-1}, did not change significantly with location or with the predominant crop establishment method used in the ISUs (data not shown). These implied that soil puddling (in WSR and TPR culture) did not significantly affect the S&P rate of the study area. This could be due to the high clay content and compacted subsoil layers associated with marine sedimentation of study soils. The inherent low conductivity of the subsoil controlled the S&P rather than the puddling.

In our water balance calculation, we used the average S&P rate of 2.5 mm d^{-1} to compute the S&P during days with standing water in the field. Figure 4 shows that the S&P amount during land preparation in TPR-ISU was about 100 mm higher than in WSR-ISU. S&P during land preparation was very low (15 $\pm$ 6 mm) in DSR-ISU. On the other hand, S&P during the crop growth period was lower in TPR-ISU than in WSR- and DSR-ISU. Findings conformed with the long period of land preparation and short crop growth period of TPR. The low S&P during land preparation in DSR-ISU was also attributed to the absence of the standing water layer during this period.

Over the whole crop season, TPR-ISU had the highest S&P, followed by WSR-ISU and DSR-ISU (Fig. 4). The higher S&P amount of TPR- and WSR-ISU came mainly from increased S&P during land preparation.

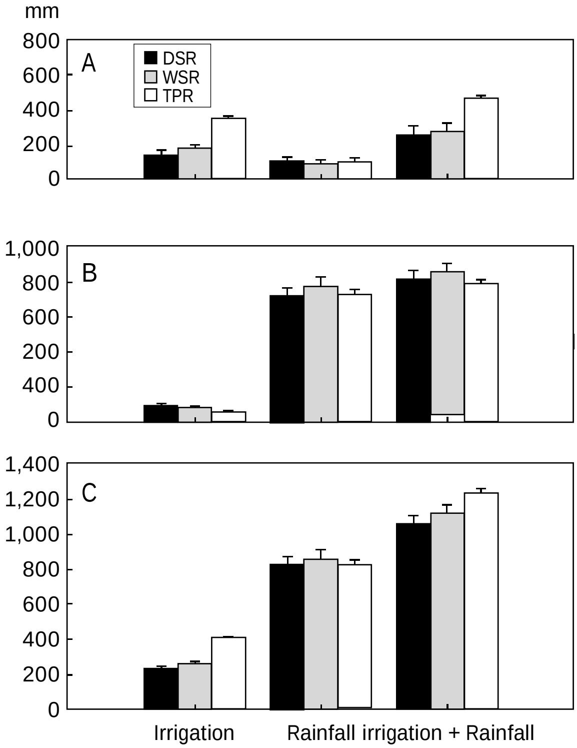

Fig. 3. Evaporation from nonrice area (E) and evapotranspiration from rice area (ET) during the (A) land preparation period, (B) crop growth period, and (C) whole crop season in irrigation service units established by dry-seeded rice (DSR), wet-seeded rice (WSR), and transplanted rice (TPR), 1988-94, Muda Irrigation System, Malaysia.

Storage and drainage

Since farmers drained the field at harvest, there was no change in surface storage over the whole crop season. Groundwater storage increased by 40–70 mm over the whole crop growth period, with most of it occurring during land preparation. There was no significant difference in change in groundwater storage among different methods of crop establishment (data not shown).

Drainage, the closure term in equation 1, was 203 ± 62 mm for DSR-ISU, 136 ± 40 mm for WSR-ISU, and 371 ± 97 mm for TPR-ISU. High standard error values masked differences caused by different crop establishment methods. A high standard error also indicated the high uncertainty of the computed drainage.

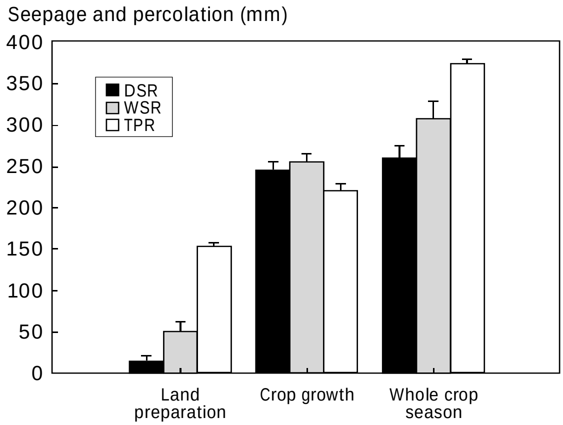

Fig. 4. Seepage and percolation in irrigation service units established by dry-seeded rice (DSR), wet-seeded rice (WSR), and transplanted rice (TPR), 1988-94, Muda Irrigation System, Malaysia.

Table 3. Means ± standard error of grain yield, water productivity with respect to irrigation (WP_I), total water input (WP_{I+R}), evapotranspiration from rice area + evaporation from nonrice area (WP_{ET+E}), and evapotranspiration from rice area (WP_{ET}), Muda Irrigation System, Malaysia.

Parameter	DSR-ISU[a]	WSR-ISU	TPR-ISU
Yield (t ha^{-1})	4.28 a ± 0.12	4.33 a ± 0.18	4.59 a ± 0.34
WP_I (kg m^{-3})	1.52 a ± 0.32	0.85 b ± 0.06	0.69 b ± 0.08
WP_{I+R} (kg m^{-3})	0.27 a ± 0.01	0.26 a ± 0.01	0.24 a ± 0.02
WP_{ET+E} (kg m^{-3})	0.41 a ± 0.01	0.39 a ± 0.02	0.37 a ± 0.02
WP_{ET} (kg m^{-3})	0.52 a ± 0.01	0.51 a ± 0.01	0.56 a ± 0.04

[a]In a row, means followed by the same letter are not significantly different at the 5% level by least significant difference.

Rice yield and water productivity

The mean grain yield of TPR-ISU was higher than that of WSR-ISU and DSR-ISU, but differences among grain yields were not significant at the 5% level (Table 3). Water productivity of the amount of irrigation water was significantly higher in DSR-ISU than in TPR-ISU and WSR-ISU. WSR-ISU had a higher WP_I than TPR-ISU but this was not significant at the 5% level. The higher WP_I in DSR- and WSR-ISU was mainly attributed to their lower amount of irrigation water (Fig. 2C). When rainfall was included, water productivity in total water input (WP_{I+R}) was significantly reduced (to about 0.26) and there was no significant difference among the ISUs.

Water productivity of depleted water (WP_{ET+E}) was higher in DSR-ISU and WSR-ISU than in TPR-ISU, but not at the 5% level of significance. The lower E + ET in DSR- and WSR-ISU (Fig. 3) was balanced by their lower yields compared with TPR-

ISU (Table 3). Rice yield per unit ET (WP_{ET}) of DSR-ISU was about the same as that of WSR-ISU and was lower than WP_{ET} in TPR-ISU. The difference was not significant at the 5% level because of a large variation in WP_{ET} of TPR-ISU.

General discussion and conclusions

The transplanted rice system in the Muda Irrigation System is representative of many irrigation systems in Asia. Farmers set aside a small area of their main fields to make the seedbeds. Because of a lack of tertiary and field channels, and with field-to-field irrigation, all surrounding fields have to be flooded before farmers can get water to prepare the seedbeds and irrigate the seedlings. Farmers thus begin soaking the land as they start seedbed preparation and do not complete plowing and harrowing until the seedlings are ready. In some cases, land soaking starts even before farmers are ready for their seedbeds because neighboring farmers prepare their seedbeds earlier. This results in a prolonged duration of land preparation and subsequent high values of E and S&P during this period. The irrigation amount during the land preparation period was approximately double that during the crop growth period (Fig. 2).

Wet seeding of rice provides an option to shorten this duration and significantly reduces the nonbeneficial E and S&P before rice is established. The crop growth period in the main field of TPR, however, is shorter than that of WSR, resulting in lower E, ET, and S&P during this period. At our study site, the "gain" during the land preparation period of WSR outweighed the "loss" during the crop growth period. This resulted in significantly lower irrigation and total water input in WSR than in TPR. This confirmed findings by Bhuiyan et al (1995) for the Philippines, where, as in Indonesia (Syamsiah 1998), seedbeds are scattered in the main fields. Transplanted rice cultivation, however, does not necessarily always require a longer land preparation period than wet-seeded rice. In some cases, seedlings are grown with good water control in community seedbeds that can be irrigated separately and land preparation of the main fields can be carried out independent of seedling age (Tuong 1999). Seedlings can also be raised in plastic trays (Tang, this volume). In these conditions, replacement of TPR by WSR will lead to significantly longer field duration so that irrigation will have to be supplied during the crop growth period in the main field and higher water input will be needed for WSR. Thus, WSR does not always lead to water savings. The advantage of WSR over TPR depends on the balance between the reduction in depletion and outflow during land preparation and the increase of the same during crop growth.

Dry seeding advances crop establishment, does not require presaturation irrigation for wet land preparation, and shortens the land preparation period considerably compared with WSR and TPR. These lead to a significant reduction in evaporation, seepage and percolation, and the amount of irrigation water during land preparation in DSR compared with the WSR and TPR systems. Early crop establishment helped DSR use early rainfall more effectively during the crop growth period than WSR and TPR. The reduction in irrigation water is compensated for by the increased amount of rainfall.

The success of the direct seeding technology in reducing the amount of irrigation water thus depends on adequate and reliable early season rainfall to ensure early crop establishment. In our study, dry-seeded rice systems had the same mean seepage and percolation rates as TPR and WSR systems, despite the lack of soil puddling in the DSR system. This may be due to the high clay content and compacted subsoil layers associated with marine sedimentation of study soils. The inherently low conductivity of the subsoil controlled S&P rather than puddling. Puddling is needed, however, to reduce the percolation rate of many other soil types. In these soils, dry land preparation may mean that puddling did not reduce the percolation rate. Increased water input because of higher percolation may outweigh water savings during land preparation. The advantage of DSR over the WSR and TPR systems depends very much on rainfall and soil characteristics.

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Notes

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Nutrient management of direct-seeded rice in different ecosystems of eastern India

H.C. Bhattacharyya, V.P. Singh, and K. Borkakati

Direct seeding of rice is practiced in all rice-growing environments. It is the only crop establishment technique used in the uplands, is very common in deep and very deepwater areas, and is becoming increasingly popular in traditionally transplanted rainfed and irrigated lowlands. Seeds are broadcast, drilled, or dibbled into dry soil in the uplands and into dry, wet, or puddled soil in the lowlands. Because the crop is established directly from seeds as opposed to transplanting, early growth and root development of direct-seeded rice encounter different soil conditions from those of transplanted rice. Direct-seeded rice is subject to diverse and heterogeneous soil environments as opposed to the more uniform conditions encountered by transplanted rice, for which flooding and puddling ensure a more uniform seedbed. Differences also exist among different ecosystems (upland, rainfed lowland, irrigated lowland, deepwater) in soil type, land preparation, and method of direct seeding. Thus, nutrient management options developed for traditional transplanted rice are unlikely to be suitable for direct-seeded rice. A major difference is in N fertilizer management. In aerobic soils, nitrate is the dominant form of N for plant uptake, unlike in anaerobic soils, where the ammonium form of N is dominant. When sown and grown in an aerated soil environment, rice roots and root hairs develop unhindered, the rhizosphere is acidified by root exudates, and, thus, the young rice plants can efficiently extract P and use soil nitrate, which is mineralized during land preparation. Thus, the recovery of soil N is higher in early growth of direct-seeded rice. Phosphate studies show that P applied at seeding or soon after (but not later than the active tillering stage) and absorbed during tillering is most efficiently used for grain production. Thus, the better ability to extract P at the early growth stage of direct-seeded rice should improve grain production. Direct-seeded rice is also reported to be efficient in using applied as well as residual K. A major factor that influences nutrient use in direct-seeded rice is soil moisture. In rainfed environments, a direct-seeded crop is often subject to periods of drought. Thus, the timing (split dressing) and form (controlled release) of fertilizer application are major issues in direct-seeded rice, especially in the lowlands.

Direct-seeded rice (DSR) differs from transplanted rice in terms of crop establishment as well as subsequent crop management practices. Direct seeding can be dry or wet; in dry seeding, seeds are broadcast, drilled, or dibbled into dry soil, whereas, in wet seeding, pregerminated seeds are broadcast or drilled into wet puddled or nonpuddled soil. In wet-seeded rice, the soil is usually kept flooded during the entire crop cycle, while in dry-seeded rice, the soil remains aerobic as in the uplands or is submerged permanently or periodically later in the crop cycle as in rainfed lowlands. The crop then starts as an upland crop but completes its crop cycle as wetland rice, or goes through alternate wetting and drying. Thus, direct-seeded rice is subject to a variety of soil aeration conditions.

In the uplands, direct seeding is the only viable crop establishment technique. Similarly, in deep and very deepwater areas, direct seeding of deepwater or floating rice varieties is the common method of crop establishment because soon after the onset of rainfall there is a sudden accumulation of water to depths that do not permit transplanting. With the availability of short-duration varieties and better water and weed management methods, direct seeding is also becoming popular in traditionally transplanted rainfed and irrigated lowlands (Singh and Bhattacharyya 1989). Economic factors relating to labor, production technologies, and increased cropping intensity have also increased the desirability of direct seeding (Pandey and Velasco, this volume).

Nutrient management issues in direct-seeded rice, particularly in the lowlands, have received very little attention until recently. With the availability of fertilizer-responsive semidwarf modern rice varieties, additional knowledge on nutrient management aimed at increasing and stabilizing yields of direct-seeded rice, especially in stressed environments, has been generated. Likewise in upland rice, awareness of the need for nutrient management research is increasing.

This paper reviews nutrient management implications of direct-seeded rice in different ecosystems. It makes suggestions for improving rice yield and nutrient-use efficiency in direct-seeded rice and indicates future research needs.

Nutrient management in direct-seeded rice

Understanding nutrient management issues specific to direct-seeded rice, particularly in rainfed and irrigated lowlands, is becoming important because of the continuous expansion of area under this culture.

Rainfed lowlands

Approaches to nutrient management of direct-seeded rice in rainfed lowlands depend on rainfall patterns, methods of direct seeding, soil type, and soil/crop management. Rice soil in aerobic and reduced phases greatly differs in physical and chemical characteristics. Since nutrients are delivered to the roots primarily by mass flow and diffusion, the lower moisture content in the aerobic phase reduces the nutrient supply to the roots (Ponnamperuma 1975). When the soil becomes wet or reduced, initial rapid mineralization of soil organic matter occurs, releasing relatively significant amounts of available N, which later on may be immobilized and rendered unavailable for crop absorption. In aerobic conditions, the end product of organic matter decomposition is the highly mobile nitrate ions, which may be easily lost by leaching and denitrification upon subsequent flooding. Thus, the loss of applied N could be high in soils under alternate drying and flooding situations.

On the other hand, dry direct seeding in the lowlands allows increased use of the conserved dry-season soil nitrate by the rice crop. In single- or double-cropped rice lands, nitrate accumulates in the soil during the extended dry season and is lost upon flooding for wet-season transplanted rice (George et al 1992). Dry seeding rice before the onset of rains enables the crop to use this soil nitrate. Further, soil nitrate as well as legume-fixed N can be accumulated in a postrice legume crop (George et al 1993, 1994) for economic use (legume grains) or recycled to a direct-seeded rice crop by establishment before the onset of rains (Patil et al 1998, 2001, Singh et al 1999).

Most nutrient research on direct-seeded rice in the rainfed lowlands is on N. An analysis across 14 locations of the All-India Coordinated Rice Improvement Project indicated that N application to direct-seeded lowland rice was beneficial only up to 40 kg N ha^{-1} (Rao 1984). Likewise, Mahanta (1993) reported a yield response only up to 40 kg N ha^{-1} by a short-duration direct-seeded summer rice in Assam (Table 1). Optimum N rates would be expected to vary, however, with soil fertility and seasonal conditions. In many studies, split N application to synchronize with periods of the most efficient use by direct-seeded rice has been found to be advantageous. Deka and Bhattacharyya (1994) found that applying 40 kg N ha^{-1} in three equal splits, with the latter two splits applied at panicle initiation and heading, resulted in higher grain yield and higher N accumulation (Table 2) irrespective of application time of the first

Table 1. Effects of levels of N on mean grain yield (t ha^{-1}) of direct-seeded lowland summer rice cv. Kalinga III (Mahanta 1993).

N levels (N ha^{-1})	1987	1988	Pooled
Control	1.1	2.1	1.6
20 kg	1.4	2.6	2.0
40 kg	1.9	2.7	2.3
60 kg	2.2	2.8	2.5
CD[a] (0.05)	0.33	0.26	0.24

[a]CD = critical difference.

Table 2. Effect of time of N application on grain yield and N content in grain and straw of direct-seeded lowland summer rice (Deka and Bhattacharyya 1994).

Time of application[a]	Grain yield ($t\ ha^{-1}$)	N content (%)	
		Grain	Straw
1/2 at 20 DAE + 1/2 at 45 DAE	1.5	1.39	0.81
1/3 as basal + 1/3 at tillering + 1/3 at PI	1.5	1.49	0.82
1/3 at tillering + 1/3 at PI + 1/3 at heading	2.1	1.66	0.98
1/3 as basal + 1/3 at PI + 1/3 at heading	2.0	1.58	0.96
1/3 as basal + 1/3 at tillering + 1/3 at heading	1.6	1.53	0.89
CD (0.05)	0.4	0.11	0.10

[a]DAE = d after emergence, PI = panicle initiation, CD = critical difference.

split. Linwattana (2001) reported the highest grain yield, crop growth parameters, and N uptake by direct-seeded lowland rice consistently across seasons and varieties when 60 kg N ha^{-1} was applied in three splits—15 kg each at 15 and 30 d after emergence (DAE) and the remaining 30 kg ha^{-1} at 45 DAE or at panicle initiation. Other split combinations produced significantly lower yields.

For P, the usual recommendation for rice is a basal application regardless of the form and application method (Singh et al 1991). Patil et al (1998) observed that direct-seeded rice performs better than transplanted rice at lower P application levels. This better performance has been attributed to more efficient P extraction because of the lowering of the rhizosphere pH to about 4 by rice root exudates under aerobic conditions. In anaerobic puddled soil, root exudates might be ineffective because of dilution in excess water. Further, young roots in the rice plant develop fine root hairs in aerobic soil, which may further contribute to better P use (Singh et al 1999, Patil et al 2001).

Legumes are known to acidify the rhizosphere by exuding organic acids, thereby making soil P more available. Thus, when grown on soils rich in calcium phosphate, legumes may meet their own P needs from the soil. If grown in rice systems on a regular basis, legumes may have significant effects on the P nutrition of direct-seeded rice through solubilization of calcium phosphate. Higher biomass production and more effective extraction of soil P via rhizosphere acidification and the formation of fine root hairs may induce P deficiency, as observed in Japan (De Datta 1986). Thus, nutritionally poor soils could become deficient in P faster if it is not applied to direct-seeded rice.

In direct-seeded rice, using rock phosphate as a cheaper source of P even in neutral soils may be an advantage, particularly when a legume is included in the system. The use efficiency of P in a rice cropping system can be improved markedly by choosing a proper crop sequence and the crop to be supplied with P in that sequence (Alam and Ladha 1997). The use of rock phosphate in a direct-seeded rice–legume system needs further evaluation.

Table 3. Effect of levels and time of potassium application on grain yield and K uptake by direct-seeded lowland rice (Kalita 1993).

Treatments[a]	Grain yield ($t\ ha^{-1}$)	K uptake ($kg\ ha^{-1}$)
Levels of K_2O ($kg\ ha^{-1}$)		
20	2.1	86.82
40	2.4	96.88
60	2.5	105.44
CD (0.05)	0.22	10.44
Time of application		
Full basal	2.3	84.82
1/2 basal + 1/2 at tillering	2.4	103.76
1/2 basal + 1/2 at PI	2.4	101.22
1/2 tillering + 1/2 PI	2.3	95.71
CD (0.05)	ns	12.05

[a]PI = panicle initiation, CD = critical difference, ns = nonsignificant.

Research on the response of direct-seeded lowland rice to K is limited. Reported responses are specific to the existing crop-growing conditions in the season. Mahanta (1993) observed a response by direct-seeded rice to 60 kg $K_2O\ ha^{-1}$ in the first year, but no response in the second year. Under similar conditions, however, Kalita (1993) found a yield and K uptake response up to 40 kg $K_2O\ ha^{-1}$ (Table 3). Likewise, Singh et al (1991) observed good responses to applied K up to 36 kg ha^{-1}.

The response of direct-seeded lowland rice to applied fertilizers varies with season. In on-farm trials in Assam under the Indian Council for Agricultural Research (ICAR)-IRRI collaborative program, yield responded to full application of 60-30-30 kg N-P_2O_5-$K_2O\ ha^{-1}$ in 1990, whereas in 1991, the response was limited to half that rate (IFAD 1992). As was mentioned earlier, the key to nutrient management in direct-seeded rice is the basal application of P and some application of N at panicle initiation and heading (IFAD 1992). Results of studies on fertilizer management practices for lowland dry direct-seeded rice showed that the recommended full basal application of P, half N and K at 15 days after sowing (DAS), and the remaining N and K at 45 DAS was on a par with the application of full P and K and half basal N, with the remaining N applied at 45 DAS (IFAD 1992). The rates of inorganic fertilizer application can be lowered when fertilizers are applied with organic manure, such as farmyard manure (FYM) or green manure. Results of experiments conducted at the Regional Agricultural Research Station, Diphu, Assam, on direct-seeded summer rice (Anonymous 1998) indicated that although the highest yield was obtained by applying 100% of the recommended NPK (40-20-20 kg ha^{-1}) along with 10 t ha^{-1} farmyard manure (Table 4), the highest benefit-cost ratio without sacrificing grain yield was obtained by reducing the application of NPK to 50% of the recommended amount with 10 t ha^{-1} FYM. Decreasing NPK up to 50% along with the reduced level of FYM applied considerably lowered yield compared with the recommended NPK alone.

Table 4. Effects of combination of farmyard manure (FYM) and NPK on direct-seeded lowland (ahu) rice at Diphu, Assam, India (Anonymous 1998).

Treatment	Grain yield pooled over 3 y ($t\ ha^{-1}$)	Benefit-cost ratio
Control	1.4	–
100% NPK	2.4	3.07
100% NPK + 2.5 $t\ ha^{-1}$ FYM	2.6	3.34
50% NPK + 2.5 $t\ ha^{-1}$ FYM	2.0	2.21
100% NPK + 5 $t\ ha^{-1}$ FYM	3.0	4.13
50% NPK + 5 $t\ ha^{-1}$ FYM	2.2	3.39
100% NPK + 10 $t\ ha^{-1}$ FYM	3.6	5.31
50% NPK + 10 $t\ ha^{-1}$ FYM	3.5	7.72
150% NPK	3.4	4.34
CD[a] (0.05)	0.29	–

[a]CD = critical difference.

Irrigated lowlands

Because the soil is puddled and anaerobic, fertilizer response of direct-seeded rice in irrigated lowlands is expected to be similar to that of transplanted rice, but different from rainfed lowlands in terms of N and P dynamics and their availability to the crop. However, few nutrient studies comparing direct-seeded and transplanted rice in irrigated lowlands exist. Research at the Central Rice Research Institute (CRRI), Cuttack, showed that both wet-seeded and transplanted rice responded similarly to N at rates below 80 kg N ha^{-1}, but wet-seeded rice yielded higher than transplanted rice at 80 kg N ha^{-1} (CRRI 1983). Similarly, Bhattacharyya and Singh (1992) reported yield responses of up to 80 kg N ha^{-1} for varieties Pusa 33 and Pusa 312 when wet-seeded; yield increased from 19% to 67% (Table 5). As in rainfed lowlands, increase in yield and N uptake were also greater in irrigated lowlands with four splits of N, the fourth split being delayed until heading (Table 5). The timing of the first split at sowing or the early vegetative (seedling) stage seemed unimportant. Usually, a basal dose of N is not effective because young seedlings do not need much N and much of the N is lost before significant uptake. Wet direct-seeded rice also exhibited the same response to P as N. Saikia and Balasubramanian (1998) reported a significant response to P in Assam, where yield was significantly higher with 50 kg than with 37.5 kg P_2O_5 ha^{-1}. As expected, they found yield to be the highest with single superphosphate as the P source (Table 6). Unlike for the rainfed lowlands and uplands, the application of rock phosphate only or the combined application of rock phosphate and phosphobacteria was not effective in irrigated direct-seeded rice. Apparently, direct-seeded rice in irrigated lowlands does not have the advantage of acidification through root exudates. Applying rock phosphate enriched with FYM (0.75 t ha^{-1}) resulted in yields similar to that with 37.5 kg P_2O_5 ha^{-1} as superphosphate. When FYM-enriched rock phosphate was applied together with phosphobacteria, yields were identical to those of 50 kg P_2O_5 ha^{-1}. Both these treatments indicate P solubilization through organic acids and enhanced root growth, thereby contributing to better P uptake and increased grain yield.

Table 5. Effect of level and time of N application on yield and N uptake of irrigated direct-seeded rice (Bhattacharyya and Singh 1992).

Treatment[a]		Grain yield (t ha^{-1})		N uptake (kg ha^{-1})	
		1986	1987	1986	1987
N (kg ha^{-1})	40	3.3	3.9	67.80	79.02
	80	3.8	4.3	82.51	98.99
CD (0.05)		0.06	0.14	2.99	5.75
Time of N application	Basal + 30 DAS + 45 DAS	3.4	3.9	70.79	85.06
	10 DAS + 30 DAS + 45 DAS	3.4	4.0	72.59	86.04
	Basal + 30 DAS + 45 DAS + 60 DAS	3.7	4.2	79.00	92.60
	10 DAS + 30 DAS +45 DAS + 60 DAS	3.7	4.2	78.05	92.33
CD (0.05)		0.09	0.20	4.23	ns
Control vs rest	Control (no N)	3.0	2.4	51.08	49.37
	Rest	3.6	4.1	75.15	89.01
	CD (0.05)	0.09	0.21	4.49	8.62

[a]DAS = days after sowing, CD = critical difference, ns = nonsignificant.

Table 6. Effect of source and level of P on grain yield of irrigated direct wet-seeded rice, Tamil Nadu, India (Saikia and Balasubramanian 1998).

Treatments	Grain yield (t ha^{-1})	
	1993	1994
Levels of P_2O_5 (kg ha^{-1})		
37.5	4.2	4.6
50.0	4.8	5.0
CD (0.05)	0.21	0.27
Source of P		
Single superphosphate	4.8	5.2
Rock phosphate (RP)	4.3	4.5
RP + phosphobacteria (PB)	4.3	4.6
RP enriched with FYM	4.6	4.8
RP enriched with FYM + PB	4.8	4.9
CD (0.05)	0.21	0.24

The recommended NPK fertilizer dose for direct-seeded rice can be reduced by half, with green manure incorporated instead (Singh et al 1987). Yield at half the recommended NPK level (50-25-25 kg ha^{-1}) together with *in situ* incorporation of sesbania (*dhaincha*) or green leaf manuring with *Leucaena leucocephala* was equal to or greater than the yield with the recommended NPK (Table 7). Green manuring in direct-seeded rice is facilitated if crop planting is done in rows.

Table 7. Integrated nutrient management of irrigated direct-seeded rice (Singh et al 1987).

Nutrient management[a]	Grain yield (t ha^{-1})		
	1984	1985	1986
Full fertilizer (100-50-50)	3.7	4.7	3.4
Half fertilizer (50-25-25)	2.7	3.3	2.7
Half fertilizer + GM (*dhaincha*)	4.0	5.2	3.4
Half fertilizer + GLM (*Leucaena leucocephala*)	3.8	5.2	3.3
CD (0.05)	0.12	0.17	0.14

[a]GM = green manure, GLM = green leaf manuring, CD = critical difference.

Deepwater areas

Soils in deepwater areas (usually alluvial) are generally fertile, but some may have salinity and acidity problems. Farmers in these areas grow traditional varieties, scarcely apply any nutrients, and their yields are usually less than 1 t ha^{-1}. Reports indicate the usefulness of applying fertilizers in these systems. Investigations carried out at CRRI, Orissa, indicated that a basal application of 40 kg urea N ha^{-1} increased plant vigor, enabling the crop to better withstand excess water stress and yield higher (CRRI 1983). Experiments conducted in Bangladesh showed that applying 80 kg N ha^{-1} and 45 kg P_2O_5 ha^{-1} produced more vigorous plants that tillered earlier and more profusely. In two of six experiments with mixed stands of deepwater and *aus* rice (Table 8), fertilizer application increased the total yield by 32% (Catling and Islam 1979). In *ahu* (autumn) and *bao* (deepwater) mixed rice cropping, which is often practiced by very deepwater rice farmers to harvest the ahu crop before the floodwater rises, line sowing gave better yield at an intermediate level of fertilizer application (30-15-15 kg ha^{-1} of N, P_2O_5, and K_2O). Split application of urea—50% basally applied (broadcast and incorporated) and the remaining applied either on the soil or as a foliar spray—was as good as the full dose applied basally (CRRI 1983). Split application of fertilizer is also not possible in deep and very deepwater areas since the water level starts rising with the onset of monsoon rains and soon after becomes too deep to apply any fertilizer. Fertilizer, especially N, must therefore be applied on the subsurface and in one application at seeding. Even plowing in broadcast-applied fertilizer just before seeding increased grain yield substantially by 0.4 t ha^{-1}, or 25% higher than yields commonly obtained by farmers in medium-deepwater situations (Rao 1984). In dry-seeded deepwater rice, urea can be applied in furrows to enhance fertilizer-use efficiency and to increase yields.

Gradual N supply or making some N available to the crop at or near the reproductive stage could be very useful to direct-seeded rice in deepwater areas. Controlled-release sources of N offer this option. In deepwater rice, applying neem-coated urea, FYM-incubated urea, and urea-placed mud balls (Table 9) 90 d before harvest when the floodwater has receded increased grain yield considerably (Anonymous 1998). Puckridge et al (1991) obtained similar results with the use of urea supergranules (USG) and basal incorporation of urea in Thailand. The management aspects of other nutrient elements in these situations were seldom studied.

Table 8. Yield response of deepwater rice (aman) and aus rice to fertilizer application at Elliotganj, Bangladesh (Catling and Islam 1979).

Location/season	Yield (t ha^{-1}) Fertilized	Yield (t ha^{-1}) Nonfertilized	Increase[a] (%)
Elliotganj I			
Aus	0.7	0.3	154**
Aman	2.7	2.0	37 ns
Aus + aman	3.4	2.2	50*
Elliotganj II			
Aus	1.9	1.4	35*
Aman	2.7	2.4	12 ns
Aus + aman	4.6	3.8	21 ns
Combined I and II	4.0	3.0	32**

[a]** = significant at P = 0.01, * = significant at P = 0.05, ns = nonsignificant.

Table 9. Effect of N management on grain yield of deepwater rice (Anonymous 1998).

Treatment	Yield (t ha^{-1})
No nitrogen	2.4
Neem-coated urea (NCU) applied basally at 30 kg N ha^{-1}	2.6
NCU at 90 d before harvest (DBH)	3.7
NCU 1/2 basal + 1/2 at 90 DBH	2.9
Mud-ball placement at 90 DBH	3.0
FYM-incubated urea placement at 90 DBH	3.2
Prilled urea 1/2 basal + 1/2 at recession of flood	3.0
CD (0.05)	0.16

Uplands

Because of the inherently low nutrient status of the soil, rice in the uplands needs fertilization more than that in the lowlands. The response of rice to fertilizer application under upland conditions (Lal 1986) depends on initial soil fertility, the previous crop grown, moisture availability, and seasonal conditions. Genotypes also show differential responses to fertilizer. The yield and dry matter accumulation of dwarf varieties increase because of the addition of N fertilizer, but tall upland varieties do not always respond to fertilizers economically (Singh and Mishra 1987). Likewise, the N response of upland rice varies with location (Table 10, Sharma and Krishnamohan 1985).

An increase in grain yields with N application in the uplands has been reported up to 40 kg N ha^{-1} (Krishnarajan et al 1984, Singh et al 1986). Increased N application raised the total dry matter production but not plant height, panicle number, and grain yield (Singh et al 1986). Increasing N alone from 40 kg ha^{-1} has reportedly

Table 10. Response of upland (direct-seeded) rice to nitrogen (Sharma and Krishnamohan 1985).

Region	Grain yield (t ha^{-1})	
	Without N	With N (80 kg ha^{-1})
Dehradun, Uttar Pradesh (UP)	2.8	3.8 (12.4)[a]
Varanasi, UP	1.3	2.7 (17.8)
Rewa, UP	1.6	3.5 (22.7)
Ranchi, Bihar	1.4	2.6 (15.8)
Bhubaneswar, Orissa	1.4	2.5 (13.7)

[a]Numbers in parentheses are response per kg N.

raised N accumulation in plants and percentage N in harvested parts, but it decreased percentage absorption, absorption efficiency, and harvest index (Tanaka et al 1984). Such responses could be attributed to poor partitioning ability of the genotypes, imbalances in other nutrient elements, or water stress.

Similar to what occurs in other ecosystems in the uplands, the split application of N fertilizer is also effective in increasing N-use efficiency (Singh and Modgal 1978, Mahapatra and Srivastava 1984). Generally, yield responses were better with three splits (Murty et al 1986, Ram et al 1985). The split application of urea was equally effective with controlled-released fertilizers such as USG or sulfur-coated urea (Kohle and Mitra 1985).

Green manuring has also been shown to benefit rice in the uplands. Perennial legumes such as *Sesbania sesban, S. grandiflora*, and *L. leucocephala* could be grown on field bunds, contour bunds, or in relay cropping, with the green matter used as green manure (Arunin et al 1994). However, farmers prefer cash crops to green manure. Where land topography and soil moisture deficit increase the risk of cash crop production, prerice green manures could be included (Garrity et al 1994). The economic value of green manure could be enhanced by using species that provide food as well, such as broadbean, green pea, mungbean, common vetch, and pea vines (Chen 1994). The N contribution from biologically fixed N in legumes can be used effectively by incorporating the crop residues in the soil. Such practices, which lead to more N incorporation, reportedly enhanced the disintegration of *Azolla* biomass and the subsequently more rapid release of N in upland rice than under lowland rice (Becking and Warwani 1989).

Unless P deficiency is corrected in high-clay, high P-fixing soils, the use of higher amounts of other nutrients, especially N, has lesser value (Singh et al 1986). For example, in an experiment on a P-deficient soil in the Philippines by Singh et al (1986), the combined application of 20 kg P ha^{-1} and 70 kg N with or without K had the most dramatic effect on upland rice. This treatment combination resulted in the tallest plants, greatest number of panicles m^{-2}, and highest total dry matter production compared with the control, N-only treatments, and low NPK levels. Several studies (Garrity et al 1990, Singh et al 1986, IRRI 1986) indicate the balancing effect on plant nutrition of P applied in combination with low to moderate levels of N in the acidic uplands. Applying higher levels of N without other elements and lime even with other elements may have an adverse effect on plant growth through nutrient imbalances. Adding lime in large quantities may induce iron deficiency and leaching of nitrate, and may also affect Mn and Si uptake.

Because of their low P fixation (Juo and Fox 1977), alfisols have a low P requirement for crop production and a high residual effect (Kang and Osiname 1979). For continuous cropping on deficient soils derived from acidic rocks, an initial application of 30 kg P ha^{-1} followed by 15–20 kg P ha^{-1} in subsequent years seems to be adequate, whereas soils derived from basic rocks require higher dressings (Juo and Fox 1977).

In a legume (chickpea)–upland rice (var. Aditya) rotation, in which upland rice responded significantly to P (Table 11; Narayana Reddy and Surekha 1998), chickpea had a positive rotation effect on upland rice yield even without P. The grain yield of upland rice in chickpea-grown plots was 44–61% higher in 1995 and 79–105% higher in 1996. Such a response is probably due to rhizosphere acidification, with organic acids exuded from legumes, thereby making soil P more available, as is the case in the lowlands.

Phosphate fertilizers should be applied basally or before the active tillering stage since P absorbed during tillering is most efficiently used for grain production. The split application of P is not beneficial because of the high mobility of P from old to new leaves (De Datta 1978). Phosphorus at 40 kg P_2O_5 ha^{-1} was optimum in the plateau region of Ranchi, India (Mahapatra and Srivastava 1984), and at 20 kg P_2O_5 ha^{-1} in Iloilo, Philippines (Singh et al 1991), with both soils also responding to K application. Incubating single superphosphate with compost gave a superior response than just applying them together. In these studies, basal placement of P in furrows

Table 11. Effect of direct and residual P on upland rice yield (Narayan Reddy and Surekha 1998).

Treatments	Grain yield (t ha^{-1})	
	1995	1996
No P application	2.8	1.5
Application of 20 kg P_2O_5 ha^{-1}	3.1	1.7
Application of 40 kg P_2O_5 ha^{-1}	3.6	2.2
CD (0.05)	0.22	0.18
Control (without chickpea)	1.8	0.8
No P + chickpea cv. ICCV10	2.9	1.5
No P + chickpea cv. ICCV37	2.9	1.6
No P + chickpea cv. local	2.6	1.4
20 kg P_2O_5 + ICCV10	3.3	1.9
20 kg P_2O_5 + ICCV37	3.0	1.7
20 kg P_2O_5 + local	3.0	1.5
40 kg P_2O_5 + ICCV10	3.6	2.3
40 kg P_2O_5 + ICCV37	3.8	2.3
40 kg P_2O_5 + local	3.3	1.9
CD (0.05)	0.3	0.3

was also superior to broadcast application. Both these methods—compost incubation and band placement—apparently lessened P fixation and improved P-use efficiency (Singh et al 1986, 1991).

Ultisols and oxisols in high-rainfall zones, particularly those derived from sandstone and sedimentary materials, have low K status (Juo 1981). Litter burning in shifting cultivation serves as an important source of K (Andrisse 1987). A maintenance dressing of 50–100 kg K ha^{-1} may be needed for high K-demanding crops such as rice (Kang and Juo 1983). Increasing K rates increased plant height, tiller count, panicle number, and grain yield of rice in the Philippines, but significantly only at 36 kg K ha^{-1} (Singh et al 1991). At this level, the yield increase (0.45 t ha^{-1} more than the yield in the zero-K treatment) and other growth parameters were the highest in all treatments. A minimum of 36 kg K ha^{-1} seems to be required in these soils to get a response. In soils where more than one element is limiting, a significant response can be expected only if applied amounts are higher than the minimum required (Singh et al 1976).

In areas where rice alternates with maize without adequate nutrient replenishment, soil fertility declines rapidly, although these two cereals are ecologically compatible in a crop sequence. Research on acid ultisols in Indonesia (Ismail et al 1982) showed that upland rice and maize + cassava, followed by two legume crops (cowpea and peanuts), is a productive and sustainable cropping system. It guarantees year-round ground cover and reduces soil erosion.

In the upland rice-based cropping systems where direct-seeded rice is followed by green gram and mustard under favorable conditions, the application of 100% recommended NPK levels to each component crop of the system has been found necessary to obtain an optimum equivalent yield in rice (Table 12). The pooled rice equivalent yield reduction over 3 y was 14.4%, 11.0%, and 7.2% when fertilizer was reduced by 50% in green gram, rice, and toria, respectively. Reducing fertilizer by 50% in all three crops in a sequence reduced the rice equivalent yield up to 41% (Anonymous 1997). The viability of rice production in the uplands therefore seems to rely heavily on ecologically sustainable cropping patterns. The cropping pattern itself may be an important nutrient management tool.

Table 12. Effect of fertilizer level on the performance of rice-based systems in uplands (Anonymous 1997).

Fertilizer (% NPK)			Rice equivalent yield (t ha^{-1})			
Rice	Green gram	Toria	1992-93	1993-94	1994-95	Pooled
100	100	100	7.9	4.3	6.7	6.3
100	100	50	7.1	4.1	6.2	5.8
100	50	100	6.4	3.4	6.8	5.4
50	100	100	6.6	3.7	6.4	5.6
50	50	50	4.2	4.2	2.9	3.7
CD 0.05			1.52	6.56	1.57	1.12

Summary and future research needs

In many lowland rice-growing environments, direct seeding of rice, as opposed to transplanting, is increasingly being practiced. Although direct seeding is the only crop establishment technique in the uplands, it is common in deep and very deepwater areas and is becoming increasingly popular in traditionally transplanted lowlands driven primarily by the scarcity of irrigation water. Seeds are broadcast, drilled, or dibbled into dry soil in the uplands and into dry, wet, or puddled soil in the lowlands. As the crop is established directly from seeds, early growth and root development of direct-seeded rice differ from those of transplanted rice.

Direct-seeded rice is subject to more diverse and heterogeneous soil environments than transplanted rice, for which flooding and puddling ensure a more uniform seedbed. Differences also exist among different ecosystems (upland, rainfed lowland, irrigated lowland) in soil type, land preparation, and method of direct seeding. It is obvious that nutrient management options developed for traditionally transplanted rice are unsuitable for direct-seeded rice, except perhaps in irrigated lowlands.

In aerobic soil, rice plants develop fine root hairs on young roots. It has been shown that root exudates from rice roots acidify the rhizosphere, enhancing P extraction by rice roots. N extraction is also improved because tillage for land preparation and early rains in aerobic soils enhance N mineralization and nitrate production. Direct-seeded rice seedlings thus establish well in most soils. However, varying soil moisture is a major factor that determines nutrient dynamics and nutrient uptake in aerobic soil; drought conditions will lead to poor seedling establishment and growth.

Transplanted rice, on the other hand, relies on nutrients in the well-watered nursery seedbed and, if necessary, fertilizer can be supplemented in the small nursery area to produce healthy seedlings.

Adding organic matter provides nutrients and enhances P solubilization from native soil as well as applied sources in all environments. Likewise, including a legume in a rice farming system has been shown to tremendously benefit the system in nutrient supply as well as in increasing the solubilization of native P in all direct-seeded systems. Such a practice should therefore be very valuable in direct-seeded rice farming.

It is imperative that productivity increases be achieved in upland rice as well as in direct-seeded rice in the lowlands to meet future food needs. Few attempts have been made to evolve situation-specific varieties and fertilizer management techniques in direct-seeded rice in different ecosystems. Concerted research efforts are therefore needed in the following areas:

- Identifying and characterizing lowland ecosystems and subecosystems where direct seeding is most practical and can be most productive.
- Developing nutrient management options specific to direct-seeded rice ecosystems, taking into account weeds and soil moisture fluctuations.

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Developing a direct-seeding technology package for rainfed lowland rice in Lao PDR

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Direct seeding could be a useful alternative to transplanting in rainfed areas where labor is scarce at crop establishment and early rains are insufficient to puddle the soil for timely transplanting. The status of direct-seeding technology that is applicable to rainfed lowland rice in Lao PDR is described and the research areas that require further work to develop a sound technology, particularly for central and southern Lao PDR, are highlighted. Findings from our recent work under the Australian Centre for International Agricultural Research (ACIAR)-funded project on "Plant breeding strategies for rainfed lowland rice in northeast Thailand and Lao PDR" are the basis of this paper. The experimental program examined the following areas of direct seeding: land preparation, time of sowing, seed rate and method of sowing, cultivars required, weed control measures, and labor resource requirement. In several cases, comparisons were made with the transplanting system.

The main conclusions point to the importance of the choice of correct seeding time when soil moisture conditions are adequate, using a high sowing rate, particularly in the row arrangement, and using cultivars that are high-yielding and do not lodge easily. A technology package for direct seeding developed for Lao PDR is described.

Research areas that require further work to develop sound technology packages include sowing method, particularly the development of a simple planting implement, weed control measures, identification of areas suitable for direct seeding, and a new double-cropping system based on direct-seeded rice.

Rainfed lowlands occupy 71% of the rice-growing area in the central and southern parts of Lao PDR and 69% of the rice area in the whole country (IRRI-Lao Project 1999). This central and southern region has been identified as the national priority area for increasing productivity toward self-sufficiency.

Annual rainfall in most provinces along the Mekong River valley ranges from 1,500 to 2,000 mm. A single wet-season rice crop is the basic production system and yields are reportedly from 2.5 to 3.5 t ha^{-1}. However, under nonfertilized conditions, an individual farmer's yield can be as low as 1 t ha^{-1}. Yield variability among years is high because of adverse weather and water availability conditions. Drought is a major problem for rainfed lowland rice in Lao PDR (Inthapanya et al 1995) and often in the early season it delays rice crop establishment.

Most rainfed lowland farmers currently establish rice by transplanting. Although direct seeding is not a common practice in both rainfed and irrigated lowlands in Lao PDR, it has some potential for improving rice productivity in the future. One of the main reasons for introducing direct seeding is to reduce the risk of establishment failure because of water shortage in the rice field at an appropriate transplanting time. Another reason is that in some areas labor is inadequate for transplanting during peak cultivation periods. Because of water shortage, transplanting is often delayed, subsequently reducing yields. In some cases, transplanting fails completely.

Direct seeding fails as a result of poor establishment caused by inadequate soil moisture at seeding time. Similarly, high levels of standing water can cause poor germination in direct-seeded rice. In low-lying areas or heavy clay soil with poor drainage, excessive moisture at seeding can result in poor establishment in direct seeding.

The objectives of the ACIAR study on direct seeding are to develop a direct-seeding technology package for rainfed lowlands in Lao PDR and to compare the merits of the new technology with those of the traditional transplanting system. The direct-seeding technology package includes suitable genotypes for direct seeding, optimum time of direct seeding, and an appropriate method for weed control and plant spacing and density.

Experiments

Thirteen direct-seeding experiments, grouped under crop management practices and genotype requirements, were conducted in the past 4 years in Lao PDR under ACIAR funding. These were conducted at three locations at research stations or in neighboring farmers' fields in Vientiane (VTN), Savannakhet (SVK), and Champassak (CPK).

In 1996, an experiment was conducted to identify the most appropriate time of direct seeding for good crop establishment and high grain yield at three sites (VTN, SVK, CPK). Seeding times were 5 May, 20 May, 5 June, 20 June, and 5 July. Three common varieties were used—Phon Ngam1, Thadokham1, and RD6. Seeds were dibbled with a spacing of 25 × 25 cm at a seeding rate of 120 kg ha^{-1}. A control experiment with the normal transplanting method was also established on 12 July 1996 to compare the differences in crop performance between direct seeding and transplanting.

Weed control experiments were conducted at the three sites (VTN, SVK, and CPK) in the 1997 wet season (WS). The experimental design was a split plot with land preparation as the main plots (2) and weed control treatment as subplots (5). The two main plots were prepared either twice or three times at 15-d intervals prior to direct seeding. During land preparation, the rice field remained without standing water. The five weed control treatments were one hand weeding at 15 d after seed dibbling (day 15); two hand weedings at days 15 and 30; rotary weeding at day 15; two rotary weedings at days 15 and 30; and the control (no weed control).

An experiment was conducted at the same three locations in 1998 to investigate the effects of plant density on grain yield under direct seeding. The split-split-plot design with three replications was used for weed control, variety, and spacing treatments as the main plots, subplots, and subsubplots, respectively. There were two levels of weed control (weeded and nonweeded), two genotypes (IR57514-PMI-5-B-1-2 and IR66368-CPA-P1-3R-0-1), and three plant densities. The plant density treatments used 25 × 25-cm and 25 × 10-cm spacing and the continuous rice rows had 25 cm between rows. Seeds were dibbled at the rate of 80 kg ha^{-1} on different dates at the three locations.

Several experiments were conducted to identify plant genotypes that would be suitable for direct seeding. The first set of experiments in the 1997 WS compared 18 genotypes at two sites, VTN and CPK.

Another experiment was conducted in the 1998 WS to investigate genotype requirement and weed competition in VTN and CPK. Twelve genotypes were selected (including seven genotypes used in 1997) to test their performance under weeded and nonweeded conditions at those locations.

A direct-seeding technology package

This section describes a direct-seeding technology that is used for rainfed lowland rice in Lao PDR, based on experiments described above and from other information. Some experimental results are included to indicate how the technology package has been developed.

Land preparation and time of seeding

The results of the time-of-seeding experiments indicated that rice direct-seeded early in the season generally yielded higher (Fig. 1). The optimum time for direct seeding appears to be late May and early June. This is earlier than the seeding time in the nursery for the transplanting system. If quick-maturing, photoperiod-insensitive cultivars are used, however, direct seeding in late May is likely to be too early as the crop matures well before the end of the rainy season. This often causes rodent problems and harvest difficulties, resulting in yield loss and poor grain quality. ACIAR-funded experiments conducted in Thailand also support this conclusion.

Land preparation to achieve adequate seedbed conditions is important for good and even seed germination. Rice fields need to be leveled more thoroughly than required for transplanting so that the soil moisture level is uniformly adequate within a field for crop establishment. The work in Cambodia clearly shows the advantages of land leveling even in small fields (CIAP 1998).

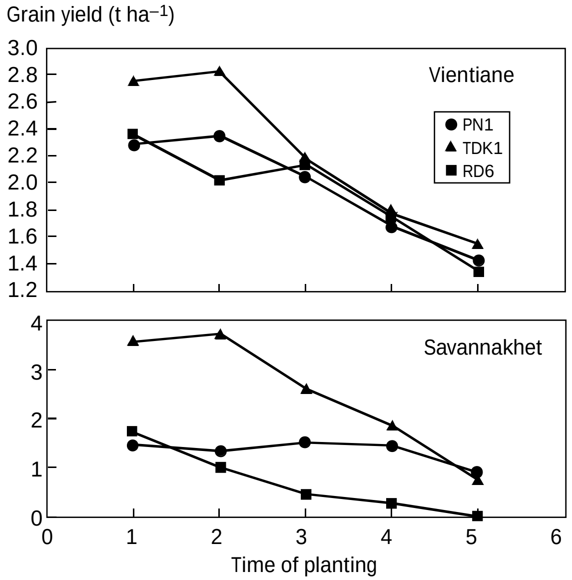

Fig. 1. Effect of direct-seeding date (1: 5 May, 2: 20 May, 3: 5 June, 4: 20 June, 5: 5 July) on grain yeild of three cultivars (PN1, TDK1, and RD6) grown in Vientiane and Savannakhet, Lao PDR.

Early land preparation is necessary for seeding early in the season. It needs to start as soon as possible after the rainy season begins. The use of a small tractor allows farmers to plow the land earlier than the current common practice of using a buffalo.

Our experiments showed that preparing the land twice was sufficient at all three locations in Lao PDR where weeds were not a major problem in rainfed lowland fields (Table 1). However, a more thorough land preparation is required in fields where weeds are likely to be a serious problem.

Seeding and crop establishment

Although the optimum seeding time may be late May or early June, seeding may be delayed if soil moisture conditions are not adequate. It is important to seed when the soil is sufficiently moist for good germination. If the soil is too wet and particularly if there is standing water in the field, the water needs to be drained before seeding. It is desirable for direct seeding to be practiced in fields where drainage is good.

Broadcasting and harrowing to incorporate seed require less labor than dibbling, but crop establishment is often not even, thus causing weed problems and a subsequent yield reduction. Dibbling seeds into a small hole, on the other hand, is likely to result in a more reliable crop establishment. Dibbling is time-consuming and there is a need to develop a simple implement to speed up the planting operation.

Table 1. Grain yield (t ha^{-1}) of direct-seeded rice under two or three land preparations before seeding at three locations (Vientiane, Savannakhet, Champassak) in Lao PDR, 1997.

Land preparation	Vientiane	Savannakhet	Champassak
2 times	2.1	3.7	2.9
3 times	2.2	4.0	2.6
Significance (5%)	ns[a]	ns	ns

[a]ns = not significant.

Table 2. Grain yield (t ha^{-1}) under three different plant spacings in weeded and nonweeded conditions at three locations (Vientiane, Savannakhet, Champassak) in Lao PDR, 1998 wet season.

Location	Spacing (cm)	Weeded[a]	Nonweeded
Vientiane	25 × 25	2.0 b	1.6 a
	25 × 10	2.0 b	2.1 a
	25 × row	3.1 a	1.9 a
Savannakhet	25 × 25	1.7 b	1.7 b
	25 × 10	2.3 a	2.6 a
	25 × row	1.9 b	1.6 b
Champassak	25 × 25	1.5 b	0.9 a
	25 × 10	1.9 a	1.1 a
	25 × row	2.0 a	1.0 a

[a]Yield is the means of two genotypes. Yields with a common letter are not significantly different at 5% for a given weeding condition and location.

Broadcasting, as commonly practiced, results in weed control problems, whereas regular row planting is advantageous for manual and mechanical weed control. Continuous rows where seeds are dropped in shallow furrows that are 25 cm apart may facilitate weed control. This also requires less labor for planting. Wide spacing between hills, on the other hand, is likely to cause more weed problems. In Vientiane, yield was higher in the row-seeded rice crop than in the dibbled crop at 25 × 25-cm and 25 × 10-cm spacing under weeded conditions, but it was similar among the three treatments under nonweeded conditions. These results suggest that the conventional spacing of 25 × 25 cm used in transplanting is unlikely to be optimum for direct seeding (Table 2). Dibbling at 25 × 10 cm is good for achieving high yield and weed control, but it requires more labor. Thus, it is advisable to establish a sound method for row seeding using a simple tool.

At all three locations, the 25 × 25-cm spacing had the most weeds and produced the lowest yields. The 25 × 10-cm spacing was better than continuous rows in Savannakhet, where high seed rates were used. In Champassak, yields from 25 × 10-cm plots and continuous rows were similar under both weeded and nonweeded conditions (Table 2).

Weed control

In rainfed lowlands where water management is poor, weed problems are more severe with direct seeding than with transplanting. In our experiments, one hand weeding was sufficient where weeds were not a serious problem (Table 3). However, weeding once may not be sufficient in areas with many weeds. Rotary weeders were more effective than hand weeding in controlling deep-rooted weeds. Results showed that grain yield among the three sites differed partly because of weed competition. Weed growth was low 15 d after seeding and weed management had no effect on fresh weed weight at the three locations. However, weed management methods (weeding twice) in Vientiane and Champassak experiments did have an effect (data not shown). The second weeding at 30 d after dibbling effectively reduced grass weed weight at Champassak. In Vientiane, weed competition affected grain yield (Table 3). At this location, it is estimated that, with no weed control measure, yield was reduced by 47% compared with one hand weeding and by 51% compared with two hand weedings.

For direct seeding, it is necessary to select fields where weeds are unlikely to be a major problem. If weeds are not expected to be a serious problem, thorough plowing and harrowing before direct seeding are required to suppress weed growth. In the experiment with the land preparation treatment, plowing and harrowing three times reduced fresh grass weed weight at Vientiane (data not shown).

Cultivar requirement

Cultivars that usually produce high yield under transplanting conditions are also suitable for direct seeding. Yield of direct-seeded rice can be as high as that of transplanted rice if better crop establishment and weed-free conditions are achieved.

Improved photoperiod-insensitive cultivars developed for transplanting conditions are likely to be suitable also for direct seeding. Figure 2 shows the relationship between yield of 12 genotypes under transplanting and direct seeding at Vientiane in 1998. Tall genotypes IRUBN-8-4-TDK-1-1 (5) and NSG 19 (8) had much lower yield under direct seeding than under transplanting because of a high lodging tendency. Similar results were demonstrated at Champassak. Lodging is a major problem in direct seeding because the high plant density commonly used in direct seeding

Table 3. Yield (t ha^{-1}) of direct-seeded rainfed lowland rice under different weed control measures obtained at three locations in Lao PDR, 1997.

Weed control treatment	Vientiane	Savannakhet	Champassak
Nil	1.1	3.8	2.4
Hand weeding once	2.1	3.6	2.8
Hand weeding twice	2.3	3.9	2.9
Rotary weeding once	2.5	4.0	2.9
Rotary and hand weeding	2.7	3.9	2.9
LSD (5%)	294	ns[a]	ns

[a]ns = not significant.

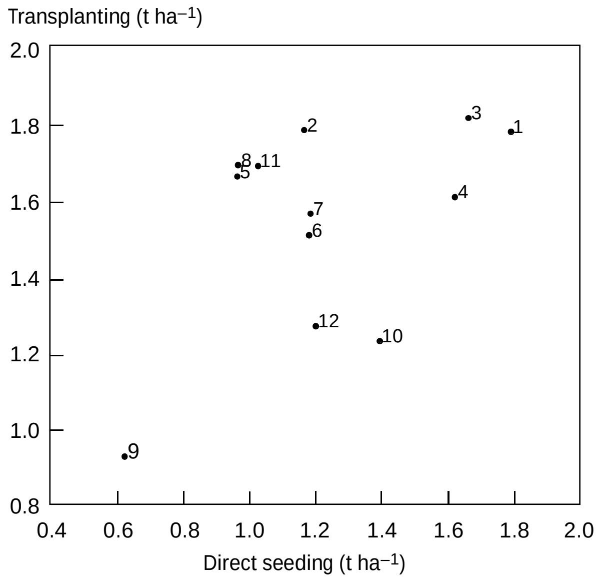

Fig. 2. Relationship between yield of 12 genotypes under transplanted and direct-seeded systems at Vientiane during the 1998 wet season.

causes excessive stem elongation, resulting in thin stems. In direct seeding, seeds are planted at shallow depths and thus the root system provides relatively poor anchorage compared with transplanted rice. Tall traditional cultivars are unlikely to be suitable for direct seeding as they are generally low-yielding and tend to lodge more.

The crop should mature around the end of the rainy season (mid-late October). Crops are commonly seeded earlier in direct seeding than in transplanting, and thus they mature earlier, particularly if photoperiod-insensitive genotypes are used. Sufficient moisture may be left in the soil for a quick-maturing legume or vegetable crop to be planted immediately after harvesting rice. Early maturing genotypes, however, may not be suitable in areas where weed competition is severe, as they may not have sufficient time to recover from weed competition and their yield is likely to be reduced. The 1998 field experiment showed that more intensive weed control might be required when early maturing genotypes are used.

Areas suitable for direct seeding

The study demonstrated that yield of direct-seeded rice can be as high as that of transplanted rice as long as the crop is established well and weeds are controlled. In experiments at Surin, northeast Thailand, Naklang et al (1996) showed that yield was higher in direct seeding (broadcasting) than in transplanting in 1992, when establishment was excellent in direct seeding. In 1994, however, there was a problem with establishing direct-seeded rice, resulting in slightly lower yield than for transplanted rice.

Direct seeding is a useful alternative to transplanting in rainfed lowland rice as it can reduce the labor requirement. Another advantage is the reduced risk of water shortage in fields at the appropriate transplanting time, which is a major problem caused by drought in rainfed lowlands in Lao PDR.

Direct seeding is thus likely to be adopted in areas where labor is not adequate for transplanting (e.g., near large cities) and where the chance of having no standing water for transplanting is high (e.g., marginal rainfall areas). It is likely to be more suitable than transplanting in fields located in upper terraces where drainage is good and soils contain a high proportion of sand.

Another potential advantage of direct seeding is the increased chance of planting another crop immediately after harvesting rice. Direct-seeded rice is often planted early in the season and hence is harvested early when soil moisture is still available for another crop. Favorable areas with a high chance of double cropping may be suitable for direct seeding.

Farmers with fields in high and reliable rainfall areas or in low topographical positions may be better off using transplanting as these fields tend to have more water available. On the other hand, irrigated areas may be converted more readily to direct seeding as good water control associated with irrigation means that weeds can be controlled more readily in irrigated areas.

A major problem of direct seeding is poor crop establishment due to inadequate soil moisture at seeding. Another common problem is the high level of standing water at seeding time that causes poor germination. Furthermore, fields in low-lying areas or with heavy clay soils and poor drainage have a high probability of having excess moisture at seeding, and hence are risky for direct seeding.

Future research requirements

Reliable and simple planting methods are required to achieve good crop establishment. Developing a simple planting tool will help promote the adoption of direct-seeding technology in Lao PDR.

The appropriate timing and rate of fertilizer application need to be identified. The nutrient requirement of direct-seeded rice is probably lower than that of transplanted rice during early growth stages. However, with higher planting densities used in direct seeding, a higher fertilizer rate may be required, particularly for later growth stages (Dingkuhn et al 1991).

A double-cropping option is worth examining where a legume crop can be planted immediately after rice if soil moisture is adequate. Sandy soils may be more suitable for establishing legumes, but limited water availability during legume growth may cause a problem during later growth stages (Kirchhof and So 1996).

Areas where direct seeding is likely to be appropriate need to be identified, based on information on soil type, topography, and probability of lack of standing water at the appropriate transplanting time. Farmers in these areas may be the focus of extension programs that promote the direct-seeding technology.

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Influences of changing from transplanting to direct seeding on the status of some pest species

T. Wada

Changes in farming practices from transplanting to direct-sown rice affect pest status. The main factors that influence pests are longer exposure of young seedlings, longer plant duration in the field, and high plant density. One of the most important economic pests in direct-sown rice is the apple snail, *Pomacea canaliculata*. The apple snail feeds avidly on young seedlings. Germinating seedlings are more than 200 times more susceptible to damage by the snail than transplanted seedlings. Sometimes, no rice plants are established in water-seeded fields because of heavy snail contamination. Drainage after sowing greatly reduces rice damage since it immobilizes the snails. Approximately 90% of plants were established when fields were drained for 2 wk after sowing compared with fields without snails. Three weeks of drainage can almost prevent damage by snails when the plant is at the 5-leaf stage. Increasing the drainage period, however, exacerbates weed problems. Fortunately, because of recent developments in herbicides, it has become possible to keep rice fields drained for 2 wk or so. But simply adopting drainage does not always solve the problem. If the drainage of residual water is insufficient, snail infestations can spread rapidly. Making ditches or ridging can enhance drainage, but neither seems to be fully successful.

Brown planthopper (BPH) *Nilaparvata lugens* and whitebacked planthopper (WBPH) *Sogatella furcifera* are threats to direct-sown rice if paddies are poorly managed, for example, by abusing the use of nonselective insecticides. According to studies of planthopper populations conducted in direct-sown rice in the Muda area of West Malaysia, population growth patterns were basically similar to those in transplanted fields. Planthoppers produce two consecutive generations and a third optional generation, depending on interactions between planthoppers and their natural enemies. But, two planthopper species displayed different preferences for certain rice stages during their migration. WBPH macropters invaded fields of

germinating rice, resulting in a population buildup. Thus, WBPH sometimes increased tremendously in fields with very young plants. WBPH caused hopperburn, although it is very rare, in direct-sown fields in Malaysia, which has never happened in other South Asian countries where a majority of fields are transplanted. On the other hand, the BPH invasion always peaks 30–50 d after sowing, which seems to suggest that a longer plant duration has no influence on direct-sown rice.

Various types of direct sowing are being studied in Japan. Among them, seed sowing on submerged rice fields is the most promising for stable production. In this method, seeds are coated with an oxygen provider and, sometimes, pesticides for plant protection. This new method will be presented in this paper.

Although transplanting is still the main method of propagating rice, the use of direct seeding has gradually increased in Asia, mainly because of rising labor costs (Morooka and Yasunobu 1993). This tendency is especially pronounced in Malaysia, Vietnam, and the Philippines. Although direct seeding has not spread to Japan, it is being studied and its use is encouraged to reduce rice production costs. Besides saving labor, direct seeding reduces irrigation water needs and shortens total growing time, sometimes enabling farmers to implement double-cropping (Pandey and Velasco, this volume). Therefore, the use of direct seeding will probably continue to increase in Asian countries.

A change from transplanting to direct seeding may affect the status of various pests. The main factors that influence pest status are (1) exposure of very young seedlings to pests, (2) longer plant duration in the field, and (3) increasing plant density. This paper describes possible changes in pest status and control strategies for some pest species in direct-seeded rice fields.

Changes in pest status

One of the most important economic pests of direct-seeded rice is the apple snail *Pomacea canaliculata*. The apple snail was introduced into Asia from South America for human food in the late 1970s and 1980s. However, the market could not be sustained. Abandoned snails soon escaped into the wild and began to attack rice voraciously. Now, this snail pest is distributed in rice ecosystems of most countries in Southeast Asia and East Asia (Halwart 1994, Wada 1997, Baker 1998).

The snail feeds avidly on young, soft rice. As rice grows, however, it gradually becomes resistant to the snail. Since very young seedlings are exposed to snails in direct-seeded fields, there is much more damage here than in transplanted fields. In transplanted rice, snails with shell heights of more than 15 mm infest rice seedlings (Oya et al 1986). Three weeks after being transplanted, plants are no longer damaged by the snails (Kiyota and Sogawa 1996). According to Yamanaka et al (1988), each snail with a shell height of 21, 31, and 40 mm consumes daily 1.7, 3.7, and 6.6 plants at the 3.1-leaf stage, respectively. On the other hand, in direct-seeded fields, even a hatchling with a shell height of 3–4 mm infests germinated seedlings and damages rice (Table 1). An adult snail causes tremendous damage to very young seedlings. For example, a snail with a shell height of 24 mm fed on more than 400 seedlings of germinating seeds, which finally failed to establish (Table 2). Germinated seedlings are 200 times more susceptible to damage by the snail than transplanted seedlings. Direct-seeded plants are susceptible to the snails for 3 weeks after sowing (WAS), the same as the susceptible period for transplanted seedlings. This is because a direct-seeded plant grows faster than a transplanted plant.

Table 1. Size of snail capable of feeding on young rice at various plant ages[a].

Shell height (mm)	Plant age (leaf number without an incomplete leaf)						
	Germinating seedling	Incomplete leaf	1 (3)[b]	2 (6)	3 (10–13)	4 (28–33)	5 (30–35)
Hatchling	O	X	X	X	X	X	X
5.0	O	O	X	X	X	X	X
7.5	O	O	P	X	X	X	X
10.0	O	O	O	P	X	X	X
12.5	O	O	O	O	P	X	X
15.0	O	O	O	O	O	X	X
17.5	O	O	O	O	O	X	X
20.0	O	O	O	O	O	P	X
22.5	O	O	O	O	O	O	X
25.0	O	O	O	O	O	O	P
27.5	O	O	O	O	O	O	O

[a]O = seedlings were entirely eaten by snails, P = seedlings were partially damaged, X = seedlings were not eaten/damaged. [b]Plant length in cm.

Table 2. Effect of drainage after sowing rice on reducing damage by *Pomacea canaliculata.*

Plot	Duration of drainage (d)	Snail density[a] (snails m^{-2})	Plant age[b] at irrigation (leaf no.)	Plants established at final census (S.D.) (plants m^{-2})[c]	Relative % of plants established[d]	Plant loss because of snails (no.)
A	0	2	–	0 (0) a	0	433.5
B	4	2	–	0 (0) a	0	161.9
C	7	2	1.5–2.1	15.5 (0) b	17.5	30.9
D	10	2	–	62.3 (6.0) c	70.1	9.5
E	14	2	3.6–4.1	77.5 (4.3) d	87.3	3.1
F	21	2	4.6–5.3	88.0 (2.1) e	99.2	0.9
Control	7	0	1.5–2.1	88.8 (1.8) e	100	0

[a]Snails with 22.5–25.5 mm shell heights were used in the experiment. [b]Number of complete leaves. [c]Within a column, treatments followed by the same letter are not significantly different at the 5% probability level. S.D. = standard deviation. [d]Percentage of established plants in each treatment relative to the number of established plants in the controls.

BPH and WBPH are potential threats to direct-seeded rice. An investigation of planthopper populations in direct-seeded rice fields in the Muda area of West Malaysia in 1989-90 showed that, in most cases, the population of planthoppers at each developmental stage peaked two or three times, representing the respective generations. Thus, both planthopper species usually completed two consecutive generations and a third optional generation. Population growth rates up to the second generation were high, but those from the second to third generation decreased to below 1.0, and occasionally to zero (Table 3). Importantly, the large variation in parameters reflecting population growth patterns characterized population trends in the Muda area and population growth patterns were primarily determined by the interaction between planthoppers and their natural enemies (Wada and Nik 1992). These figures are basically similar to those in tropical transplanted fields.

The two planthopper species displayed different preferences for certain rice stages during their migration. This stage for WBPH was usually 10 to 30 d after sowing (DAS). However, WBPH macropters were sometimes observed even on very young germinated seedlings, resulting in a population buildup. It is well demonstrated that population growth rates of WBPH increase when the host rice is young (Kuno 1968, Watanabe 1994). Thus, WBPH benefits largely from direct seeding and its numbers often increase markedly in young direct-seeded fields in the Muda area. WBPH causes hopperburn, although rarely, in direct-seeded fields in Malaysia, but not in other South Asian countries where a majority of fields contain transplanted rice. On the other hand, BPH did not invade very young paddies. BPH invasion usually peaked at 30 to 50 DAS. The preference of BPH for this growth stage seems to remove the influence of exposure of young seedlings and longer plant duration that characterize direct-seeded paddies.

The rice leaffolder, *Cnaphalocrocis medinalis*, does not invade very young paddies. The most suitable stage for oviposition by the moth is the early tillering stage. Thus, the change from transplanting to direct seeding probably has less influence on

Table 3. Average pattern[a] of population growth of rice planthoppers in direct-seeded paddy fields of the Muda area (mean ± S.D.)

Species	Maximum density of immigrants[b] m^{-2}	Mean density of 3–5-instar nymphs m^{-2}			Maximum density of 3–5-instar nymphs m^{-2}	Population growth rate[c]		
		1st generation	2nd generation	3rd generation		r_{01}	r_{12}	r_{23}
Sogatella furcifera	3.7 ± 7.5 (0.2–25)	32 ± 36 (6–126)	288 ± 200 (0.6–576)	129 ± 179 (0–575)	473 ± 380 (24–1,239)	22.6 ± 20.9 (1.5–63)	12.3 ± 9.0 (0.1–30)	0.4 ± 0.4 (0–1.0)
Nilaparvata lugens	18 ± 88 (0.1–159)	40 ± 63 (3–187)	187 ± 242 (36–624)	67 ± 71 (1.2–195)	365 ± 417 (39–1,131)	21.1 ± 17.2 (0.6–42)	10.9 ± 6.1 (0.3–18)	0.4 ± 0.3 (0.1–0.8)

[a]Data obtained from two or three fields during the four consecutive rice seasons of 1989 and 1990. Numbers in parentheses indicate minimum and maximum values. More details are shown in Wada and Nik (1992). [b]Maximum density of macropterous adults before 30 DAS for *S. furcifera* and before 50 DAS for *N. lugens*. [c]r_{01}, r_{12}, and r_{23} indicate the population growth rates from immigrants to the first generation, from the first to the second, and from the second to the third generation, respectively.

the occurrence of the rice leaffolder. The total growing time of rice is about 10 d less for direct seeding than when a nursery stage is included as in transplanting. Accordingly, direct seeding is disadvantageous for insect pests that do not invade very young paddies.

Increasing plant density in direct-broadcast paddy fields may affect the occurrence of insect pests. Scattered clumps of plants with high density make insecticide application difficult and incomplete, thus reducing its effectiveness. This is especially true for insect pests such as planthoppers that inhabit the basal part of the plant. Changes in microclimate may also affect the multiplication of insect pests. No field research on this aspect is available but high humidity in direct-seeded fields with high plant density probably favors planthopper multiplication because planthoppers are highly adapted to the high-humidity monsoon climate. A few reports cited more planthoppers in direct-seeded fields than in transplanted fields in the Muda area (Nik and Hirao 1987). This may be due to the microclimate effect, but it needs to be confirmed.

Control strategies

The preferred direct-seeding practice for limiting apple snails is dry seeding. Snails bury themselves in the soil or become dormant on the soil when there is no paddy water. In dry seeding, young rice plants grow under dry conditions; thus, no snail damage occurs.

In wet seeding where seeds are sown on or into puddled soil or in irrigated fields, draining the fields after sowing effectively reduces snail damage. Ninety percent of the plants (in plots without snails taken to be 100%) became established even at high snail density when the plots were drained at 2 WAS (Table 2, Wada et al 1999). Three weeks of drainage almost eliminated snail damage in plants at the 5-leaf stage. Therefore, a considerable period (2–3 wk) of drainage after sowing should be adopted in direct-seeded paddies with snails.

Weed problems are exacerbated, however, by increasing the drainage period. The development of new herbicides has made it possible to keep paddy fields drained for 2 wk or more. Even in paddies without snails, drainage after sowing has also recently been recommended for improving plant establishment when seeds are sown into the soil (Yoshinaga et al 1998).

Drainage can be effective in controlling snail damage, but simply adopting the practice does not always solve the problem. If drainage of residual water is insufficient, snail infestations can spread rapidly, especially after a heavy rain. Making ditches or ridging can enhance drainage (Fukushima et al 1998), but neither is fully successful. Evidence so far suggests that, for poorly drained fields with snails, direct seeding should not be used.

Tropical rice fields are favored by an abundance of natural enemies of rice insect pests. In particular, many reports have demonstrated that planthopper populations are suppressed by activities of their natural enemies (Kenmore et al 1984, Cook and Perfect 1989, Wada and Nik 1992). BPH outbreaks that occurred in the past three decades in tropical rice fields were often attributed to resurgence caused by the misuse of nonselective insecticides. In direct-seeded rice fields, as in transplanted fields, augmentation of indigenous natural enemies is the most important strategy for controlling planthoppers. Omitting unnecessary spraying against leaf-feeding lepidopterous larvae in the early rice stage, which is often suggested by IRRI and FAO, is one of the practical ways to achieve this (Huan et al 1999). When planthopper densities increase, only selective insecticides such as buprofezin should be used so that natural enemies can be preserved. Augmenting natural enemies and using resistant varieties are two important principles in regulating planthopper populations in the tropics.

The incidence of stem borers varies with rice type. Plants with thick stems generally favor stem borer multiplication. Stem borers *Chilo suppressalis* and *Scirpophaga incertulas* used to be two of the most serious pests in Japan. In the 1950s and 1960s, however, the change in rice varieties from the panicle-weight type to the panicle-number type (thin-stem type) and harvesters that crushed plant straws after harvest spread rapidly throughout Japan. Thereafter, stem borers disappeared from most Japanese rice fields. This suggests that the choice of rice varieties and removal of complete straws inhabited by stem borers after harvest are more important factors for stem borer management than changing from transplanting to direct seeding.

Some research implications

Although drainage is an effective way to avoid snail damage, it is often impossible during heavy rainfall or for poorly drained fields. This is essentially a problem of the infrastructure of the paddy. If paddy water can be effectively controlled, snail problems will be solved. In addition, we can greatly reduce herbicide applications because the apple snail is a promising bioagent for weeding (Okuma et al 1994). Simultaneous ditch construction or ridging using a machine was also tested in Japan to see if it would reduce snail damage to rice sown into puddled soil. This was partially effective for drainage and thus for reducing snail damage, but making sufficient ditches or ridges was difficult and the method was not fully successful. Having an effective technology for draining fields is critical to combating snails in rice fields.

Classical biological control for the apple snail deserves investigation. Introducing natural enemies of the apple snail from its origin (South America) may succeed in controlling the snails. Surprisingly, in southern Brazil where the apple snail is distributed, there are no or very few snails in most rice fields (Wada 1999). Thus, rice can be grown in wet direct-seeded fields without controlling snails although snail damage has begun to be apparent in some areas recently. The reasons why there are no snails in most rice fields are unknown. Natural enemies may work very efficiently. Most natural enemies of the apple snail that have been reported are birds and fish, but a parasitic nematode, which destroys the reproductive organs of the apple snail, has also been found in recent years (Yusa, personal communication). Why the snail density is very low in paddies of South America is a fascinating question.

Standardizing survey methods for rice insect pests in direct-seeded paddy fields, especially in direct-broadcast fields, is helping to further improve plant protection. Few reports deal with population studies of insect pests in direct-seeded fields probably because population surveys are difficult compared with those for transplanted fields. Developing easy and standard methods for each pest species will accelerate the accumulation of population data. Accordingly, we can compare data obtained form various countries and data obtained from transplanted fields.

Among various ways of direct seeding, line sowing or hill sowing rather than broadcast sowing is desirable for plant protection. In broadcast-seeded fields, farmers have difficulty monitoring the densities of insect pests and their natural enemies. Applying a pesticide is also difficult and generally incomplete. In addition, high plant density resulting in high humidity in broadcast fields accelerates the occurrence of diseases such as rice sheath blight. A line-seeder and a hill-seeding machine have been developed in Japan; however, they are expensive and not suitable for a small field. Developing a compact, cheap line-seeder or hill-seeder that can be adopted by a majority of farmers with small lands will contribute to the further spread of direct seeding in Asia.

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Weed management in direct-seeded rice in South Vietnam

D.V. Chin and M. Mortimer

The Mekong River Delta in South Vietnam is a major rice production area in which four types of direct-seeding methods are practiced: wet seeding, dry seeding, zero-tillage seeding, and water seeding. Traditional wet direct seeding remains the most popular form of cultivation, accounting for up to 60% of the area sown. Yield losses as high as 46% caused by weeds have been reported; consequently, farmer adoption of herbicides has increased rapidly in the last decade together with the wider use of alternative crop establishment methods. This paper summarizes current crop establishment and weed management practices in direct-seeded rice. The role of various land preparation practices and straw burning in reducing the weed seed bank in the long term is compared, and the impact of no-tillage systems for weed control was evaluated for both wet- and dry-seeded rice.

Rice is the major grain crop in Vietnam with more than 7 million ha sown every year. Transplanted rice predominates in North Vietnam, whereas more than 90% of the sown area in the south is direct-seeded. The Mekong Delta is the major area for rice production in the south. In 1997, 14.8 million t of rice were produced in the south, accounting for half of the national production, which contributed to the export of 3.68 million t of milled rice. Four major types of direct-seeding methods in rice are practiced: wet seeding, dry seeding, zero-tillage seeding, and dry seeding. Weeds are the major threat to crop protection in direct-seeded rice. On-farm yield losses as high as 46% caused by weeds have been reported in weed-free plots. This paper briefly reviews current agronomic and weed management practices, and options for improvement.

Crop establishment methods

Farmers use four types of crop establishment methods in relation to hydrological conditions.

Wet seeding

This is the most common method used in the Mekong Delta and the sown area may reach 60%. The percentage of wet seeding is highest in the winter-spring (WS) season followed by the spring-summer (SS) and summer-autumn (SA) seasons. Normally, the WS rice crop is established during November-December after flood recession. After natural land drainage, any standing water remaining in the fields is removed by pumping and the soil is then puddled. Rice seeds are soaked for 24 h and incubated from 24 to 36 h. Pregerminated seeds are then sown onto the soil surface at 200 to 250 kg ha^{-1}. Typically, water is reintroduced into fields for weed suppression 7–10 d after sowing (DAS). Infestations are usually lower in wet-seeded rice than in dry-seeded and zero-tilled rice.

Water seeding

Pregerminated seeds are sown directly into water depths of 20–40 cm. Farmers practice this technique on a large scale in the Long Xuyen quadrangle and the Plain of Reeds on low-elevation land, away from main river sources on characteristically acidic, poorly draining soils. Water seeding enables farmers to proceed without waiting for the floodwater recession necessary for wet seeding and to minimize the risk of late-season drought in the crop. In acid-sulfate soils, the high availability of Al^{+++} and Fe^{++} ions ensures silt deposition, resulting in transparent water in the field for successful rice establishment. Fields are drained gradually as the crop develops to a depth of 5–10 cm for much of the season. This practice substantially reduces weed infestations during early crop establishment. Farmers continue to use local rice varieties although some improved varieties for anaerobic conditions have been identified (Yamauchi 1996).

Zero-tillage seeding

After the harvest of the WS rice crop in January or February, rice straw is scattered over the fields, dried for a few days, and burned. Fields are then irrigated to an average depth of 5 cm before sowing pregerminated seeds onto the wet ash layer. Subsequent seepage, leaching, and evaporation result in water loss down to a saturated soil during the process of crop emergence. In this way, zero-tillage shortens the turnover time when cultivating three rice crops per year and also minimizes the risk of crop damage in the succeeding SA rice crop caused by early flooding at the ripening stage. Land preparation costs by this method are also reduced. Moreover, in acid-sulfate soil areas of the Plain of Reeds, farmers prefer this practice in the SA season to reduce soil acidity. However, zero-tillage results in high weed infestations, particularly of perennial weeds such as *Paspalum distichum* (Hach 1999) and insect pest predators have been recorded as significantly lower in fields where stubble is burned (Loc et al 1998).

Dry seeding

This method is practiced in the SA season when water is in short supply. Land preparation involves plowing or rotovation prior to a fallow period during the dry season in areas lacking irrigation systems or in coastal areas where soil salt concentrations are high. This fallow period may extend from February to May, but dry seeding usually occurs in April (Sam and Sang 1998). Chien et al (1997) reported that, in the 1997 SA season, the average area under dry seeding was 60%, but it was 100% on the Camau peninsula and 91% in the coastal areas of the Delta.

Yield losses caused by weeds

Yield reductions as high as 46% caused by weeds in on-farm studies have been reported in weed-free plots (Chin and Sadohara 1994). More than 400 weed species have been recorded in rice fields in Vietnam. The two most important families are the Poaceae and Cyperaceae, which constitute 42% of all weed species (total: 167). Other major families are Asteraceae (26 species), Scrophulariaceae (18 species), Fabaceae (14 species), Lythraceae (10 species), and Laminaceae (9 species) (Chin 1995). In a survey of 197 farm sites in 11 provinces in the Delta, the *Echinochloa crus-galli* complex was the dominant species (>70% of total plant density) at more than 50% of the sites surveyed, and was common (10–70%) at more than 35% of the remaining sites. *Leptochloa chinensis* and *Fimbristylis miliacea* were equally abundant at most sites and were ranked as the next most important weed species. Both were the most abundant at about 18% of the sites. *Cyperus difformis* was the dominant species at about 7% of the sites and was common at 41% of the sites. *C. iria* was much less. These five species are the dominant rice weeds in the Mekong Delta.

Weedy rice ecotypes of *Oryza sativa* are an emerging pest in direct-seeded rice in Vietnam, particularly under dry seeding (Chin 1997). In interviews of 4,397 respondents in 128 districts of 18 provinces, 64% of the farmers reported the presence of weedy rice in rice fields. Compared with cultivated forms, these ecotypes typically had a shorter duration, taller plants, weaker culms, smaller seeds, shattered more easily, and had red pericarps. These ecotypes have been postulated to have resulted from interspecific hybridization with *O. rufipogon* (Buu 1998).

Weed management

Indirect methods of weed control

Certified seed. Rice seed contamination with weeds continues to be one of the major causes of weed infestations, given the high seed rate commonly used in direct seeding. Farmers normally use a 200–250 kg ha^{-1} seeding rate. The majority (81%) keep seed for successive crops, with less than one in five exchanging seeds with neighbors or buying certified seeds (Luat et al 1998). The quality of farm seed supplies is very poor. Mai et al (1998) reported that the average number of weed seeds per kilogram of rice seeds was 466, forty-seven-fold higher than the permitted national purity level. The corresponding number for weedy rice seed was 314 seeds kg^{-1} rice seed. Regulations on the level of impurity of weedy rice seeds in rice have not yet been established in Vietnam. A government program on certified seed production to meet farmer demand was launched in 1999, but the annual percentage of certified crop seeds used by farmers in the region is currently less than 5%. As evidenced for most small grain crops (Cousens and Mortimer 1995), the use of certified seed has proved to be an essential component in weed management, especially where weed species do not possess a persistent seed bank as well as in prohibiting invasive species.

Land preparation and stand establishment. The need for thorough land preparation to ensure a vigorous rice stand and to suppress weeds is well known. Hach (1999) studied the cumulative effect of tillage practices on weed infestations and the size of the soil seed bank in wet-seeded rice over three seasons. Seven treatments were examined: (1) zero-tillage with straw burning, (2) zero-tillage without straw burning, (3) dry plowing and harrowing, (4) dry plowing and harrowing + puddling, (5) dry rotovation + puddling, (6) dry rotovation + puddling + leveling, and (7) wet rotovation + puddling + leveling. The principal weed species observed in the experimental trial were *E. crus-galli, L. chinensis, P. distichum, C. difformis, F. miliacea,* and *Ludwigia octovalvis.* The *E. crus-galli* population increased over the three seasons, but *L. chinensis* was characteristically dominant in the SA season. The highest weed densities were observed under zero-tillage with straw burning and increased over time in this treatment. The perennial grass, *P. distichum,* increased noticeably under zero-tillage without straw burning. After three seasons, the size of the buried weed seed bank (0–5-cm depth) was found to be the highest under zero-tillage without straw burning (269,009 seeds m^{-2}), followed by dry rotary cultivation (240,606 seeds m^{-2}), and the lowest under wet rotary cultivation + puddling + leveling. In the absence of additional in-crop weed management, wet rotovation + puddling + leveling gave the highest rice yield. These findings confirm the major importance of tillage practices in influencing the recruitment of weed species into irrigated rice and the concomitant need for improved in-crop weed control if zero-tillage practices are to be advocated.

Farmers in the Delta normally use a high seeding rate of 200 to 250 kg ha^{-1} in the belief that it will compensate for losses at crop establishment and suppress weeds. However, under weed-free conditions, similar rice yields can be achieved with lower seeding rates of only 75–100 ha^{-1} (Luat et al 1998). Hiraoka et al (1998) concluded that, in the absence of additional weed control, *E. crus-galli* densities were significantly reduced only at seeding rates above 200 kg ha^{-1}, whereas *L. chinensis* densities were reduced at seedling rates of 100 kg ha^{-1}. Weed populations of *C. difformis, F. miliacea,* and *L. octovalvis* at 55 d after sowing (DAS) were unaffected by seeding rate.

Drill sowing using a modified IRRI seeder has been adopted gradually by farmers in the Mekong Delta. Compared with broadcasting, it saves more than 100 kg ha^{-1} of rice seeds and minimizes losses caused by insects, diseases, rats, and lodging. Moreover, weedy rice and volunteer rice plants can be easily detected between rows of cultivated rice for easier manual removal during the vegetative stage. Quan (1999) reported a gain in rice yield under row seeding of 0.5–1 t ha^{-1} in the SA season compared with yields in broadcast rice at similar rates (because of improved stand establishment). Seedling broadcasting has also been introduced into Vietnam from China over the last 3 years and the adoption rate is highest in North Vietnam. Two advantages of this method cited by farmers are a seedling growth advantage over germinating weeds and suppression of weeds by standing water.

Water management. Chin (1995) reported that water depths ranging from 5 to 12 cm can suppress the germination and emergence of grass weeds but not sedges or broadleaf weeds. Water depths of 10–20 cm from 5 to 30 DAS reduced the emergence of *Echinochloa* spp. but not *Monochoria vaginalis*. Hach et al (1997) concluded that increased flooding depth enhanced the efficacy of early postemergence pyrazosulfuron-ethyl (20 g ai ha^{-1}) applications, a synergy not exhibited with butachlor and thiobencarb. Early flooding at 4 DAS in wet-seeded rice also reduces weed infestations, particularly *E. crus-galli* densities (Hach 1999). Compared with flooding at 14 DAS, rice yields under early flooding were 30% higher in the SA season and 15% higher in the WS season in that study. The importance of water management in weed control in direct-seeded rice is well known but water management still has to achieve its full potential in many Asian countries through improved land leveling and irrigation control (Hill et al 2001).

Crop rotation. Rotating rice with a dicotyledonous crop enables the use of graminicides, especially for weedy rice control. The use of a wider spectrum of chemical modes of action may also help delay the development of herbicide resistance (De Datta and Baltazar 1996). Farmers in central Vietnam rotate rice with mungbean in the dry season. Watanabe et al (1998) concluded that this was effective for weedy rice management since volunteer rice seedlings failed to survive in mungbean because of insufficient soil moisture. After 4 months, the average percent viable seed of weedy rice was only 27% in moist soil conditions, while in submerged soils it reached 57% (Chin et al 2000).

Direct methods of weed control

Manual weeding. Hand weeding continues to be used in rice production in Vietnam, but the majority of farmers in the south use chemical control measures. From farmer surveys, Mai et al (1998) found that 85% of the farmers hand-weeded direct-seeded rice every season from 20 to 30 DAS. The work was primarily (76%) done by women. In the absence of chemical control, farmers usually conducted three hand weedings per season in wet-seeded rice crops at 10–15, 25–30, and 40–45 DAS. Trung et al (1995) estimated that from 150 to 200 person-days ha^{-1} were required to keep rice crops free of major weeds using manual weeding alone.

Chemical control. Herbicide use in rice production has increased sharply in Vietnam over the last decade because of the increasing availability and rising cost of labor for manual weeding. There are 24 commercial products (proprietary mixtures or single compounds) formulated for rice weed control in Vietnam. Anilofos, thiobencarb, bensulfuron methyl, bispyribac sodium, butachlor, cyclosulfamuron, cyhalofop-butyl, 2,4-D; ethoxysulfuron, fenoxaprop-P-ethyl, MCPA, metsulfuron methyl, molinate, oxadiazon, pendimethalin, propanil, pyrazosulfuron-ethyl, and quinclorac are marketed as single products. Common mixtures are butachlor with 2,4-D or propanil, propanil with diflufenican or oxadiazon, and fenoxaprop-P-ethyl with 2,4-D and MCPA. The majority of these have a single trade name, but some compounds have many brand names. For example, butachlor has 17 trade names and 2,4-D has 18. Propanil is marketed with five commercial names and pendimethalin, pretilachlor, and pyrazosulfuron-ethyl each have two names. Metsulfuron methyl has been used successfully by farmers to control *Marsilea minuta.* Cyhalofop-butyl at very high rates of 160–200 g ai ha^{-1} can be spot-treated at 15–25 DAS to control *L. chinensis* in dry areas, as well as patches of perennial *P. distichum* and *E. stagnina* regrowing from stem fragments without any phytotoxicity on rice. Five registered herbicides (thiobencarb, oxadiazon, oxadiargyl, molinate, and pretilachlor) used for controlling common rice weeds also reduce weedy rice infestations (Chin et al 2000).

Bioherbicides. To minimize the dependency on herbicides to control weeds, mycoherbicides are now being studied. To date, the most promising fungi for inundative biological control of *E. crus-galli* are *Exserohilum monoceras* and *Cocholiobolus lunatus* (Thi et al 1999). Rice varieties IR50404 and CR203 were not affected by these fungi. *Setosphaeria* sp. cf. *rostrata* was also found to effectively control *L. chinensis* and not damaging to IR64. However the use of bioherbicides at the farm level and the need to develop methods of delivery remain serious constraints to adoption.

Conclusions

Direct-seeded rice in South Vietnam will continue to underpin national rice production and exports in the future. However, concerns over the emergence of herbicide resistance in direct-seeded rice in Asia (Valverde and Itoh 2001) have emphasized the need for sustainable weed management systems. Those that focus on grass weeds will be essential. While herbicide use is expected to increase significantly in the next decade in Vietnam, a range of integrated weed management strategies that optimize the use of herbicides through improved water management and cropping systems for intensive irrigated rice needs to be developed and tested by on-farm research. The production and use of clean seed will be an important component in this program, especially for controlling weedy rice.

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Weed species shifts in response to serial herbicide application in wet-seeded rice in Malaysia

Azmi Man and M. Mortimer

A long-term field study began at the MARDI Research Station, Seberang Perai, Malaysia, in 1996 to investigate changes in weed communities of wet-seeded rice in response to repeated applications of eight herbicides (2,4-D, bensulfuron, pretilachlor, quinclorac, propanil, fenoxaprop-P-ethyl, molinate + propanil, and benthiocarb + propanil) in common farm use. Rice yields and weed species abundance 60 days after seeding were assessed in eight consecutive seasons of a planned 10-season study. Rice yields declined over the initial course of the study, but on average were the highest (3.4 t ha^{-1}) in benthiocarb + propanil and bensulfuron-treated plots and the lowest (<2 t ha^{-1}) in fenoxaprop-treated plots. However, differences in yield gain arising from the use of alternative herbicides were often small in most seasons. Plots were usually dominated (> 50% proportional abundance) by a single weed species, reflecting differential responses to selective herbicides, with *Echinochloa crus-galli* being the most abundant in 2,4-D-treated plots, *Scirpus grossus* under bensulfuron, and *Monochoria vaginalis* in the remaining plots. Changes in rankings of subdominant weed species depended on season and did not indicate strong successional processes.

Weed species shifts in response to changes in rice crop establishment methods have been widely reported in tropical Asian countries with the conversion from transplanting to wet seeding (Moody 1995). In Peninsular Malaysia, this has been particularly associated with increases in grass weed infestations, especially *Echinochloa* species and *Leptochloa chinensis* (Azmi and Baki 1995), with concomitant expansion and reliance on the use of selective graminicides including fenoxaprop-P-ethyl, molinate, propanil, quinclorac, cyhalofop-butyl, and thiobencarb (Azmi and Lo 1990). Preemergence herbicide applications tend to be the most effective for grass control because of the lesser efficacy of late postemergence herbicides and the need to protect rice from weed competition in the early stages of the crop (Azmi 1994). Farmers have frequently reported seasonal variation in the abundance of weeds, including perennial species, where rice is cropped twice a year in the main season (October-February) and in the off-season (April to August). However, an alternative response of the weed flora to serial use of the same herbicide may be weed succession toward a community of species naturally resilient to the means of control (Mortimer and Hill 1999). This paper selectively reports findings from an experiment planned to monitor detailed changes in weed flora of wet-seeded rice over 10 seasons in response to widely used herbicides in Malaysian rice agriculture and to examine seasonal variation in yields and weed species composition.

Materials and methods

The experiment was conducted at the MARDI experimental station, Bertam, Penang, over eight cropping seasons from October 1996 to June 2000. In each main season, rice was direct-seeded during October and in the off-season during late April and early May.

In 1996 (off-season), land previously under intensive direct-seeded rice production was left unweeded and an area with a homogeneous weed flora was identified. Sixty days after seeding (DAS), weed samples were taken from 20 1-m^2 random quadrats and dry biomass was measured. Species ranked by dry biomass were *Monochoria vaginalis* (62%), *Ludwigia hyssopifolia* (19%), *Scirpus grossus* (5%), *Echinochloa crus-galli* (4%), and *Limnocharis flava* (4%). Less common species were *Cyperus iria* (2%), *Fimbristylis miliacea* (2%), *Scirpus juncoides* (1%), *Sagittaria guayanensis* (<1%), *Cyperus difformis* (<0.1%), *Najas graminea* (<0.1%), and *Bacopa rotundifolia* (<0.1%). Subsequently, in September 1996, 40 permanent 8 × 8-m plots were laid out; each plot was isolated by 0.5-m-high levees to prevent movement of irrigation water. A 1.0-m-wide channel between plots was used for irrigation and drainage purposes.

At the start of each season, plots were cultivated individually to prevent cross-contamination of soil. Dry tillage was carried out 15 d after the previous harvest, followed by a second tillage of saturated soil 10 d later. Leveling was done manually according to conventional farmer practices using hand tools, leaving a puddled soil devoid of weeds. Pregerminated seed of rice variety MR84 (seeding rate of 60 kg ha^{-1}) was broadcast onto saturated soil. Plots remained drained until 12 DAS, after which they were irrigated. The water depth was maintained from 0.05 to 0.10 m. In the main 1999-2000 season (season 7), plots were resown in November because of exceptional rainfall and uncontrolled flooding.

Each crop was broadcast with 100 kg N and 40 kg P and K ha^{-1}, with two-thirds of the N and all the P and K applied at 15 DAS. The remaining N was supplied at rice panicle initiation. Trebon (ethofenprox 10%) and sumicidin (fenvalerate 3%) were used for insect pest control as needed. Drat (chlorophacinone), mixed with rice grains, was placed at 3-m intervals on bunds along the perimeter of the experimental area as rat bait 1–2 d before sowing.

In each season, plots received one of 10 weed control treatments (Table 1) distributed in a completely randomized block design, with four replicates. The eight herbicides examined were chosen based on common usage by Malaysian farmers and supplied as commercial formulations. Herbicides were applied manually with a lever-operated knapsack sprayer at 250 L ha^{-1} and a spray pressure of 20–25 p.s.i.

Table 1. Weed management treatments.

Treatment	Application: Rate (kg ai ha^{-1})	Application: Time (DAS)[a]	Soil condition at time of herbicide application	Target weed species
Propanil	3.0	10	Saturated or drained	*Echinochloa crus-galli, Leptochloa chinensis*
Quinclorac	0.25	10	Saturated to standing water	*E. crus-galli*
Pretilachlor	0.1	3	Saturated or drained	*E. crus-galli, L. chinensis,* and some broadleaf weeds and sedges
Molinate + propanil	3.3	10	Saturated, drained or standing water	*E. crus-galli, L. chinensis,* and some broadleaf weeds and sedges
Benthiocarb + propanil	3.0	5	Saturated or drained	*E. crus-galli, L. chinensis,* and some broadleaf weeds and sedges
Fenoxaprop-P-ethyl	0.1	30	Standing water	*E. crus-galli, L. chinensis*
2,4-D amine	1.0	20	Standing water	*Monochoria vaginalis, Fimbristylis miliacea, Scirpus grossus, Sagittaria guayanensis, Limnocharis flava, Cyperus iria, Scirpus juncoides, Ludwigia hyssopifolia, Bacopa rotundifolia*
Bensulfuron	0.05	10	Standing water	*M. vaginalis, F. miliacea, C. iria, S. juncoides, S. guayanensis, B. rotundifolia*
Two manual weedings	(15 & 30 DAS)			
Unweeded checks				

[a]DAS = days after sowing.
Note: Soil condition at application time and target weed species are commercial recommendations for herbicide use. Combined ai's for mixtures only available.

Rice tiller counts were taken at 30, 60, and 90 DAS and at harvest. Weed biomass and number per plot were assessed at 60 (± 1 day) DAS in four 1-m^2 quadrats placed outside a central 5 × 5-m area reserved for yield determinations. After density enumeration, weeds were washed, sorted by species, dried at 80 °C to constant weight, then weighed. Yield data (at 14% moisture) were taken from the central harvest area.

Repeated measures analysis of variance with Huynh-Feldt F-ratio correction was used to analyze the variation in rice yields and weed biomass over time in relation to weed management treatments, with pairwise contrasts between means protected by Bonferonni. The significance of the rank order of weed species abundance (relative density) within seasons by treatment was assessed with Friedman's two-way analysis (Siegel 1956), and Page's trend test (Page 1963) was used to test for changes in species rank order within individual treatments over time.

Multivariate analysis (redundancy analysis) was used to quantitatively examine weed community structure in relation to season and weed management treatments. This form of multivariate ordination is similar to principal component analysis [see ter Braak (1995) p. 144 for distinction] and analyzes the abundance of species as linear combinations of habitat variables, in this case season and weed management treatments. This analysis was confined to the first four seasons since very low stand establishment was experienced in season 5. Abundance data were log transformed. Explanatory relationships between species composition and habitat variables were examined by stepwise forward regression, minimizing residual sums of squares at each step.

Results and discussion

Mean tiller densities (105 m^{-2}) were similar at 30 DAS and thereafter in all seasons with the exception of seasons 4 and 5 (off 1998 and main 1998-99). In these seasons, tiller densities were reduced to 62 and 28 m^{-2} by thrips and uncontrollable early flooding, respectively. Averaged over eight seasons, the highest grain yields were obtained with bensulfuron alone, benthiocarb and propanil, and 2,4-D; similar yields were achieved with two hand weedings (Fig. 1). Yields in fenoxaprop (applied 30 DAS)-treated plots were not significantly different from those of unweeded checks and were the lowest of all in six of the eight seasons.

Seasonal variation in yields was evident ($P \leq 0.05$) (Fig. 2). Over the first five seasons, yields in manually weeded and fenoxaprop-treated plots and unweeded checks declined with the exception of the third season. Subsequently, mean yields in seasons 6–8 were similar among treatments. Within each season, yield contrasts of individual herbicide treatments with either unweeded checks or fenoxaprop were always significant ($P \leq 0.05$) but no differences were detected among other herbicide treatments, except in season 4 (Fig. 3). In this season, which was characterized by a reduced rice stand, yield ranked by treatment in the order of benthiocarb + propanil = 2,4-D > bensulfuron > molinate + propanil = pretilachlor = quinclorac > propanil. Representative variability in weed species composition over the eight seasons was reflected by comparisons of seasons 1, 4, and 8 and the discussion is focused on these.

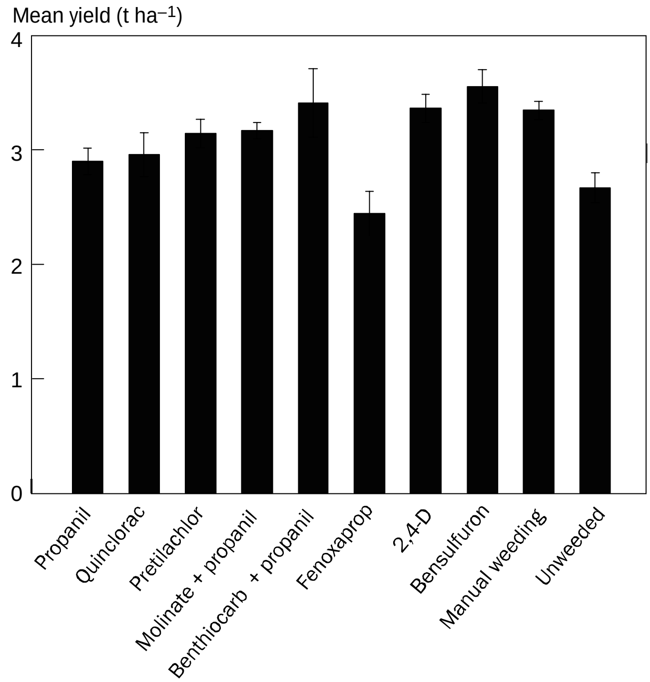

Fig. 1. Yields (mean ± SEM) averaged over eight seasons in relation to weed management treatment. SEM = standard error of mean.

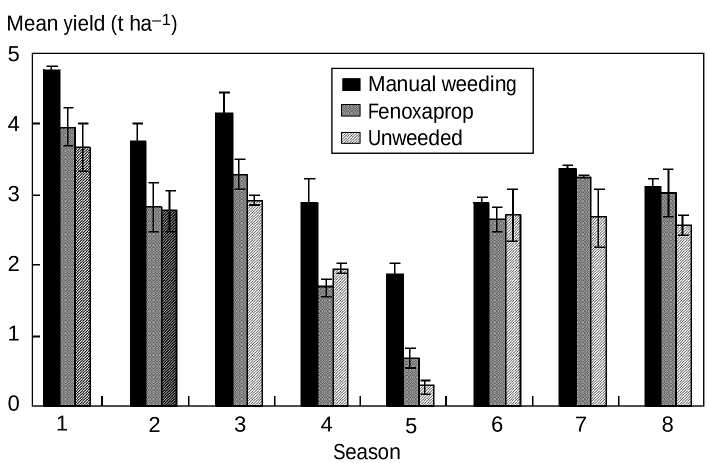

Fig. 2. Seasonal variation in rice yield (mean ± SEM) in selected plots. SEM = standard error of mean.

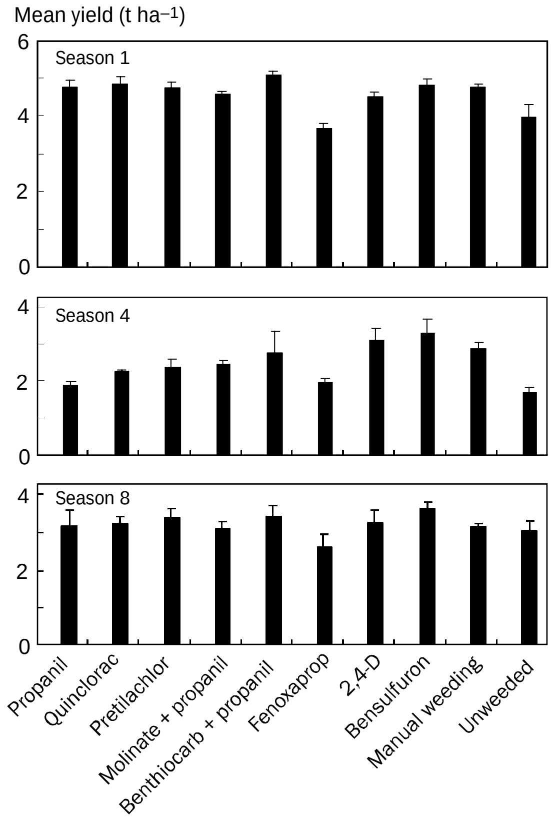

Fig. 3. Variation in rice yield (mean ± SEM) in selected seasons. SEM = standard error of mean.

Rice yield was strongly negatively correlated with weed biomass at 60 DAS in seasons 1 and 4 (respectively, Pearson $r = –0.580, –0.597$, $P \leq 0.05$) but not in season 8. In sprayed plots, the least weed biomass was recorded in plots treated with bensulfuron in all seasons (Fig. 4). Across herbicide treatments, differences in weed biomass between seasons 1 and 8 were comparatively small and approximately one-third of those in season 4.

Log rank abundance curves (proportional density) of the 11 weed species recorded at 60 DAS are given in Figure 5 for seasons 1, 4, and 8. Abundance curves were predominantly geometric or log series. Within each season, there were significant differences (Friedman $P \leq 0.05$) in the rank order of weed species because of herbicide treatments. In unweeded plots, communities were similarly structured in seasons 1 and 8, with *M. vaginalis* and *E. crus-galli* predominating and *Scirpus grossus, S. juncoides,* and *Paspalum vaginatum* ranked successively. Directional changes in the dominant weed species reflected the well-known selective modes of action of herbi-

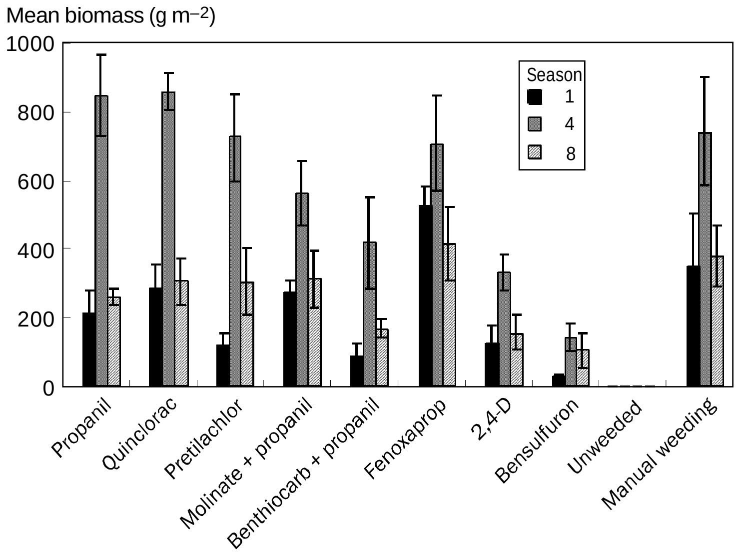

Fig. 4. Weed biomass (at 60 days after sowing) in relation to weed management treatments in selected seasons.

cides. In the first season, chemical control of broadleaf weeds with 2,4-D resulted in the dominance of *E. crus-galli*, while graminicides (e.g., quinclorac, pretilachlor, and propanil) promoted *M. vaginalis*. Bensulfuron resulted in the lowest biomass and densities (data not shown) among all weed species, with the communities dominated by *S. grossus* and *E. crus-galli*. *E. crus-galli* was eliminated by the use of fenoxaprop (Fig. 5B) by season 3, while *Scirpus* spp. and *P. vaginatum* occupied intermediate rankings in season 8. Serial application of 2,4-D retained the dominance of *E. crus-galli* and led to the exclusion of *Scirpus* spp. by season 8; other species were rare (< 1%). In contrast, the subdominant flora in fenoxaprop-, pretilachlor-, propanil-, and quinclorac-treated plots was more diverse and exhibited both *Scirpus* spp., with *P. vaginatum* occurring at low relative frequency, although prior to this (season 4) *P. vaginatum* retained a higher ranking.

In season 4, weed communities were more diverse in fenoxaprop-, 2,4-D-, and pretilachlor-treated plots than under other treatments. Benthiocarb mixed with propanil excluded *E. crus-galli* by season 8, but elevated the proportion of *Scirpus* species compared with propanil alone. The mixture of molinate and propanil suppressed the proportional abundance of subdominant weed species to less than 5%.

Within individual herbicide regimes, succession in the weed flora over seven seasons (season 5 was omitted because of poor crop establishment) was examined using Page's test. The null hypothesis that the rank order of individual species was random through time was tested against the alternative hypothesis that individual herbicides caused a selective reduction of target species (Table 2). In all instances,

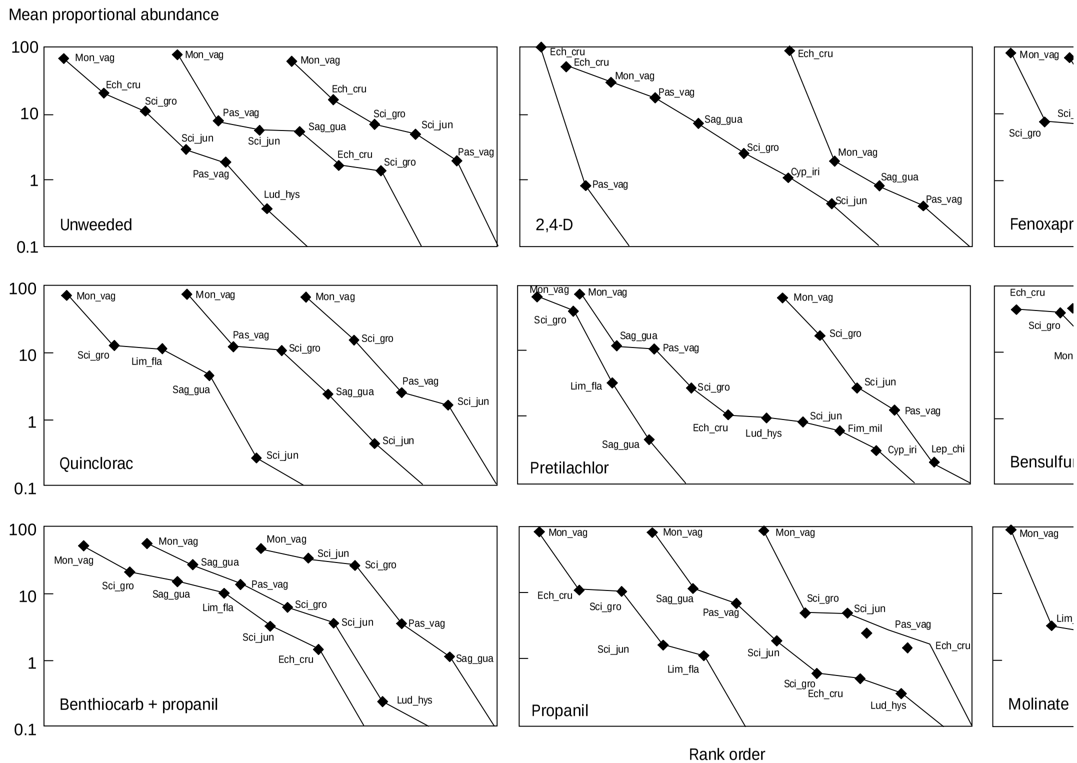

Fig. 5. Log rank abundance (density) of weed communities present at 60 days after sowing in seasons one, four, and eight, successively from the left for each herbicide treatment. Weed species names are truncated for clarity.

these tests of successional change were not significant. The ordination diagram (Fig. 6) illustrates the relative abundance of species in relation to habitat variables (treatments and seasons). The first two axes of the ordination explained 26% and 13% of the total variance in the species data (Monte Carlo permutation test, $P < 0.005$) with corresponding species-habitat correlations of 0.93 and 0.85, respectively. Table 2 ranks the explanatory power (λ_1) of each habitat variable individually in explaining species-habitat relationships, and gives the contributions (λ_2) of each variable in stepwise regression. The herbicides 2,4-D and bensulfuron and the initial growing season were equal in explanatory power when considered alone, outranking other seasonal effects that individually were more important than the remaining weed management treatments. Stepwise analysis of species-habitat relationships indicated that all habitat variables, with the exception of quinclorac and pretilachlor, contributed explanatory variance to the data set. In Figure 6, the correlation between species and habitat variables is reflected by the comparative direction of the arrows. Arrows pointing in the same direction indicate a strongly positive correlation, those in opposite directions a highly negative one, and those crossing at right angles had no correlation. While confirming the findings of log rank analysis in terms of primary responses of species to herbicides, this analysis indicates that the responses of the weed flora in seasons 1 and 3 were similar and differed from those in seasons 2 and 4.

Implications for weed management

This study has confirmed two well-established axioms in yield protection from competitive weeds in wet-seeded rice: the need for early weed control and the characteristic interspecific selection within the weed flora through the use of selective herbi-

Table 2. Summary of regression analysis of species-habitat relationships.

Marginal effects		Conditional effects			
Habitat variable	λ_1	Habitat variable	λ_2	F	$P(H_o)$
2,4-D	0.10	2,4-D	0.10	6.09	0.005
Bensulfuron	0.10	Bensulfuron	0.12	7.25	0.005
Season 1	0.10	Season 1	0.09	7.18	0.005
Season 2	0.09	Season 3	0.10	7.62	0.005
Season 4	0.07	Season 2	0.09	8.99	0.005
Season 3	0.06	Season 4	0.07	7.41	0.005
Fenoxaprop	0.06	Molinate + propanil	0.05	5.84	0.005
Molinate + propanil	0.05	Fenoxaprop	0.04	5.57	0.005
Quinclorac	0.03	Unweeded	0.02	3.07	0.025
Benthiocarb + propanil	0.03	Benthiocarb + propanil	0.02	2.80	0.015
Unweeded	0.02	Propanil	0.01	1.76	0.065
Propanil	0.02				
Pretilachlor	0.01				

Note: λ_1 is the proportion of variance explained by the habitat (season and treatment) variables when each is used as the sole predictor of species-habitat relationships (marginal effects) and λ_2 is the additional proportional contribution to explained variance by each predictor (conditional effects), fitted in the order that makes the maximum reduction in residual sums of squares at each step. P (H_o) gives the significance of the F-statistic for each addition.

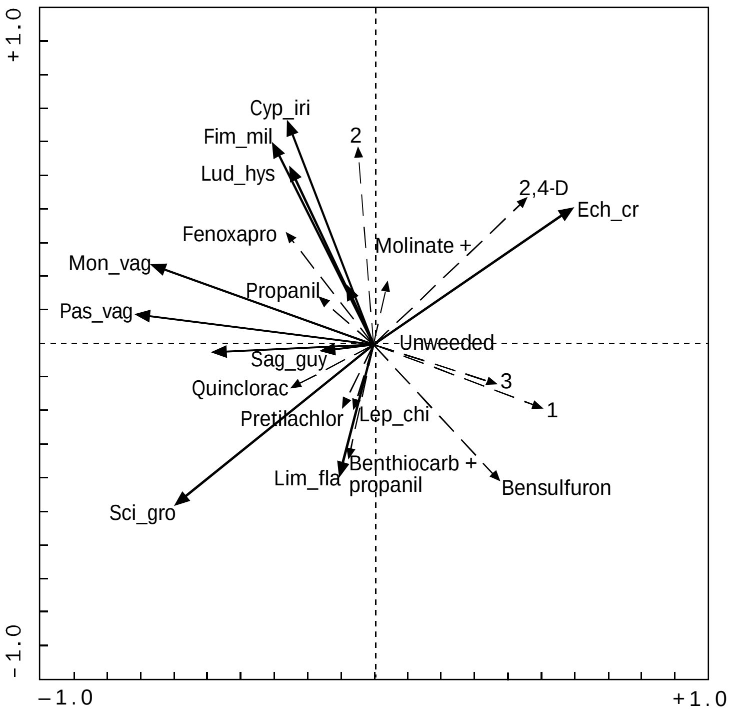

Fig. 6. Biplot diagram of the relationship between species abundance and treatments (see text for details). Species and habitat variables are indicated by arrows, the length of which reflects the strength of association with ordination axes. Weed species names are truncated.

cides. All herbicides applied prior to the first 20 DAS protected yield, unlike fenoxaprop applied at 30 DAS, which, while eliminating *E. crus-galli*, resulted in increased biomass of other weed species. In long-term rice, yields were the highest in bensulfuron-treated plots, although equivalent yield gains from other herbicide applications were achieved in individual seasons. The apparent superiority of bensulfuron in this study reflected higher yields in seasons 4 and 5 (latter data not shown) when initial rice stands were poor. Moreover, manual weeding at 15 and 30 DAS in most seasons was as effective as individual herbicide application, suggesting that replacing manual weeding with herbicides may be driven largely by economic criteria.

Figure 6 and Table 2 indicate that variability in weed species diversity was strongly influenced by differences among main (1 and 3) and off (2 and 4) seasons, besides the effects of bensulfuron and 2,4-D. This finding supports the hypothesis that temporal variation is important in arresting successional changes in response to herbicide use. Moreover, given that yield gains because of herbicides (other than bensulfuron) with differing modes of action were often seasonally comparable, seasonally driven weed species substitution may be occurring with similar net competitive effects on yield. Developing a process-based ecological explanation in support of this hypothesis and elucidating the mechanisms involved, however, will require a much greater understanding of early events in the development of the weed flora in wet-seeded rice in which herbicides are applied early in the life of the crop. This in turn will underpin the development of sustainable integrated weed management practices based on rotation of herbicide mode of action. Further findings and analysis from this experiment over the planned 10 seasons will be reported elsewhere.

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Notes

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Managing direct seeding for rainfed lowland rice with particular attention to weed control

P. Romyen, S. Khunthasuvon, and S. Fukai

This paper describes briefly the recent work on direct seeding in rainfed lowland rice in northeast Thailand funded by the Australian Centre for International Agricultural Research. Seven experiments were conducted in 1996-98 to establish a basis for developing technology for direct-seeded rice, particularly in relation to weed control. We investigated (1) seeding time for good establishment, (2) seeding rate for competition against weeds, and (3) the use of cultivars with high yield potential and vigorous growth. When the crop was planted early in the season, quick-maturing cultivars flowered too early in the wet season and yield decreased. In one experiment in which the weed population was high and no weed control was conducted throughout crop growth, a high seeding rate of 200 kg ha^{-1} was required to minimize the adverse effect of weeds. On the other hand, when weeds were controlled, a seeding rate of 100 kg ha^{-1} produced the highest yield. Cultivars with low established plant density competed poorly with weeds. Canopy structure and maturity also affected competitive ability against weeds. Quick-maturing cultivars were more affected by weeds and had greatly reduced yields. This study highlighted the overall importance of weeds in determining the yield of direct-seeded rice in the rainfed lowlands.

Rainfed lowland rice in northeast Thailand covers about 4.76 million ha. Annual rainfall varies from 1,100 to 2,300 mm (Varasoot 1985) and its distribution also varies considerably. In addition, sandy-textured soil that is predominant in the northeast has low water-holding capacity. With little irrigation water available for rice, drought is the major constraint to yield in the region. Drought occurs any time during the crop season but commonly early or late in the season (Fukai and Cooper 1995). Experimental and simulation studies estimate an average yield loss of 13–35% because of drought for rainfed lowland rice in northeast Thailand (Jongdee et al 1997, Khunthasuvon et al 1998). Early-season drought often results in a lack of standing water at the appropriate transplanting time and the crop may fail completely. This problem can be eliminated by adopting dry direct seeding (DSR). Farmers in northeast Thailand adopted DSR and planting area increased from 4.4% in 1989 to 25% in 1992 (OAE 1994). However, DSR yield was generally lower than that from transplanting in the region (1.4 vs 1.8 t ha^{-1}, OAE 1994). General cultural practices and research and development during DS in the region were reviewed by Naklang (1997).

Weeds generally compete more strongly with rice under direct seeding and when the season is dry with no standing water in the field. Thus, the main focus of managing direct seeded rice in rainfed lowlands is weed control (Moody 1982, Moody and Mukhopudhyay 1982). If weeds are not adequately controlled in the early stages of crop establishment, yield loss in broadcast rice may be severe (Upasena 1980). This series of experiments aimed to provide a basis for understanding management options for DSR, particularly in relation to weed control.

Materials and methods

In each year, experiments were conducted in two locations in northeast Thailand.

Time of planting (1996)

Two experiments were conducted to determine the optimum planting time for cultivars of different maturities. One experiment was conducted at Phimai; however, it failed because of drought. The other experiment was conducted in a farmer's field at Ban Nonsaart in Mahasarakam Province.

A split-plot design was used with planting time assigned to main plots (5) and cultivars as subplots (5). Times of planting were 27 May, 13 and 28 June, and 15 and 31 July. Cultivars used were NSG19, RD23, IR57514-PMI-5-B-1-2, KDML105, and Chiang Saen. Cultivars were selected based on a contrast in photoperiod sensitivity and time of maturity when seeded at the "normal" time in June-July. RD23 is photoperiod-insensitive and early maturing, NSG19 is mildly sensitive and early to intermediate-maturing, IR57514-PMI-5-B-1-2 is mildly sensitive with intermediate maturity, KDML105 is strongly sensitive and medium-late-maturing, and Chiang Saen is strongly sensitive and late-maturing (Immark et al 1997). Basal fertilizer was applied about 30 d after planting (DAP) at 15-30-30 kg $N-P_2O_5-K_2O$ ha^{-1} and crops were topdressed with 15 kg N ha^{-1} at 60 DAP. Weeds were controlled manually.

Cultivar performance under competition with weeds (1997)

Experiments were conducted in farmers' fields at Amphoe Nonsung, near Phimai, and Tapra, about 12 km from Khon Kaen. In each experiment, a split-plot design with four replications was used. Level of weed control was assigned to main plots (3) and cultivars as subplots (10). Each location had three levels of weed control: no weeding, partial weeding, and full weeding. Partial weeding consisted of hand weeding twice at 2 and 4 wk after emergence (WAE). At Phimai, the full weed control treatment consisted of a tank mixture of 2,4-D (dichlorophenoxy acetic acid) plus propanil

[*N*-(3,4-dichlorophenyl) propanamide] at 2.0 kg ha^{-1} applied at 2 WAE. Weeds not controlled by this herbicide treatment were removed by hand. At Tapra, the full weeding treatment consisted of an application of 2,4-D/propanil at 2 WAE plus three hand weedings at 4, 6, and 8 WAE.

Subplots consisted of 10 cultivars—IR66879-8-1-B, IR69513-14-SRN-1-UBN-1-B, IR46331-PMI-32-2-1-1, IR53466-B-118-B-B-20, IR57514-PMI-5-B-1-2, Mahsuri, RD6, NSG19, RD23, and KDML105. At Tapra, IR53466-B-118-B-B-20 was replaced by KKNUR82003-SKN-69-1-1. Seeds were broadcast at 100 kg ha^{-1} at both locations. Tapra seeds were sown on 30 June 1997 and seed germinated on 10 July 1997. Basal fertilizer was applied at 30 DAE at 15-30-30 kg N-P_2O_5-K_2O ha^{-1} and topdressing was 15 kg N ha^{-1} at 50 DAE. Since chlorosis appeared on rice leaves at around 80 DAE at Tapra, 30 kg N ha^{-1} was added to meet the N requirement of rice crops. At Phimai, basal fertilizer was applied at 100-100-50 kg N-P_2O_5-K_2O ha^{-1} and N was provided at panicle initiation using urea at 14 kg N ha^{-1}.

In these experiments, weed number was counted and dry weight of weeds was measured at 2-wk intervals until maturity from a 50 × 50-cm area. Plant samples were washed, dried at 70 °C for 48 h, and then weighed. The number of weeds in each rice cultivar plot at each sampling time was expressed relative to the mean weed number of all cultivar plots at that time. This relative weed number was used to examine the rice cultivars' ability to suppress weed growth at different times during the season.

A grain yield reduction because of weeds in unweeded and partially weeded treatments was calculated for each cultivar and is expressed as percent reduction to accommodate the variation in grain yield under fully weeded conditions.

Seeding rate (1998)

The 1998 experiments were also conducted at Phimai and Tapra using a split-split plot design with three replications. The main plots (2) were assigned to level of weed control: no weeding or hand weeding at 2 and 4 WAE at Phimai and 4 and 8 WAE at Tapra. Subplots were two rice cultivars, RD23 and KDML105. Subsubplots were five different seeding rates (50, 100, 150, 200, and 250 kg ha^{-1}) at Phimai and four rates (50, 100, 150, and 200 kg ha^{-1}) at Tapra. Plot size was 4 × 5 m. Chemical fertilizer was applied basally at 30-30-30 kg N-P_2O_5-K_2O ha^{-1} at about 30 d after emergence (DAE). A topdressing of 30 kg N ha^{-1} was applied at about 60 DAE.

Results

Time of planting (1996)

The experimental site at Ban Nonsaart had favorable water conditions throughout crop growth. No significant yield response to planting time was observed for strongly photoperiod-sensitive cultivars KDML105 and Chiang Saen (Fig. 1). In contrast, a significant yield response was observed in RD23 (photoperiod-insensitive), in IR57514-PMI-5-B-1-2 (mildly photoperiod-sensitive), and to some extent in NSG19 (mildly photoperiod-sensitive). IR57514-PMI-5-B-1-2, known to produce high yield under transplanting, produced the highest yield under direct seeding. When planted

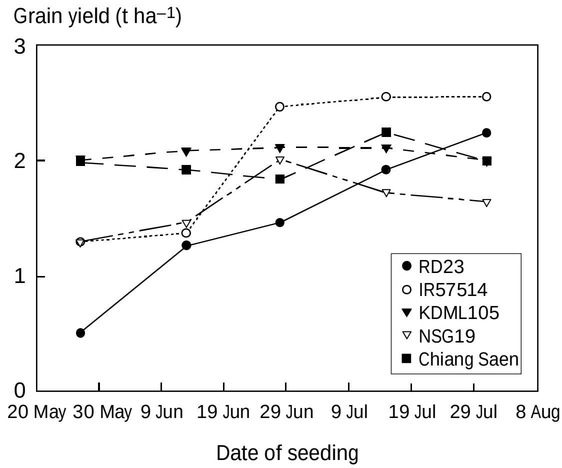

Fig. 1. Grain yield of five rice cultivars at different direct-seeding times, Ban Nonsaart, Mahasarakam Province, 1996.

early, RD23 and IR57514-PMI-5-B-1-2 flowered early, resulting in lower yields because of flowering in the middle of the rainy season, and matured well before the end of the rainy season. This led to spikelet sterility, rodent damage, and harvest difficulties, resulting in yield loss and poor grain quality. However, when these two cultivars were sown later, flowering occurred after 10 October and they produced the highest yields. Insensitive and mildly photoperiod-sensitive cultivars of early to medium maturity showed a yield advantage when planted such that flowering occurs after 10 October under favorable rainfall.

Cultivar performance under competition with weeds (1997)

Phimai. Early growth of rice was greatly affected by drought and salinity. Seedlings of all cultivars started to emerge approximately 35 DAP and reached maximum plant density at 7 DAE. Small-seeded Mahsuri produced more plants than other cultivars. Because of drought, both rice and weed growth were poor until about 10 WAE, after which they both grew rapidly.

The dominant weed species were *Ischaemum rugosum* Rotz., *Cyanotis axillaris* (L.) D. Don., and *Fimbristylis miliacea* (L.) Vahl. Other species present were *Echinochloa colona* L., *Panicum cambogiense* Balan., *Ipomoea aquatica* Forsk., *Hedyotis corymbosa* (L.) Lam., and *Fimbristylis dichotoma* (L.) Vahl.

Although relative weed number in different cultivars varied during rice growth, there were generally lower weed levels in KDML105 and IR46331-PMI-3-2-1-1 than in plots of other cultivars (Fig. 2). *Ischaemum rugosum* was suppressed by KDML105 at 8 WAE.

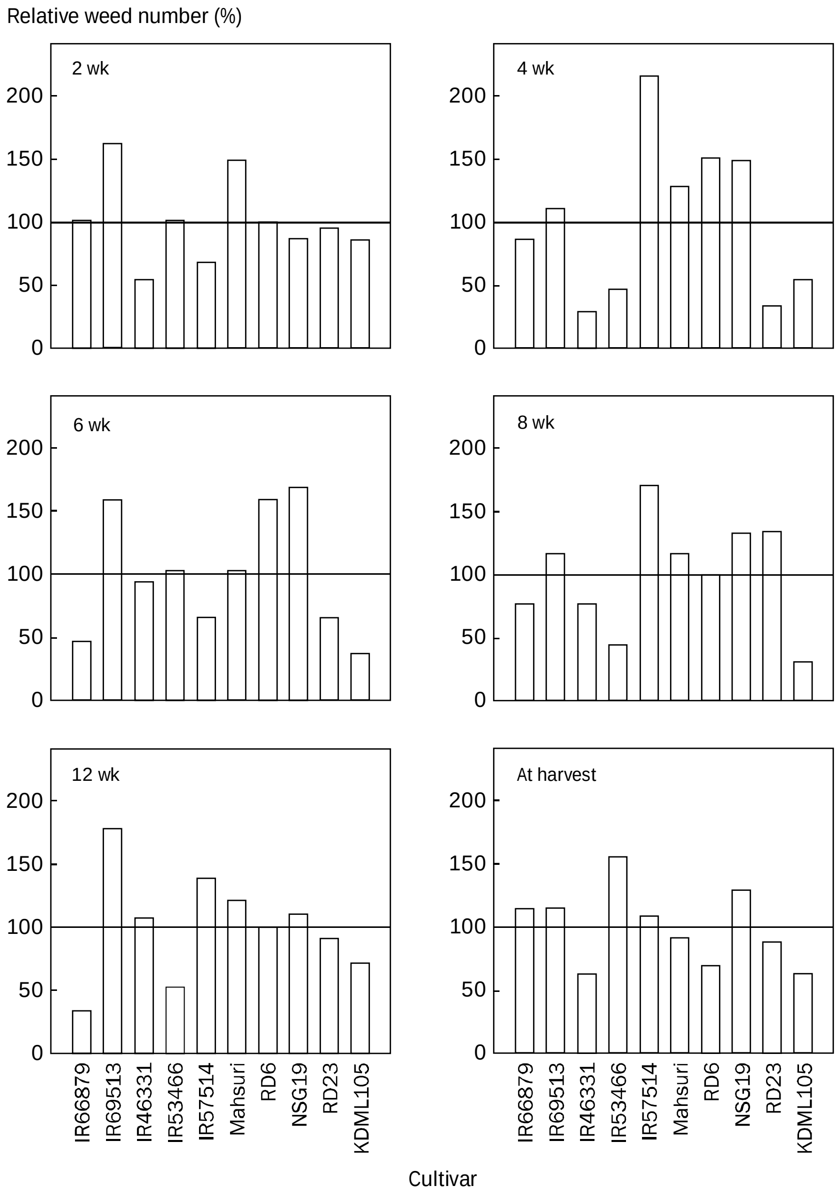

Fig. 2. Relative weed number at six different times during growth of 10 cultivars of direct-seeded rice, Phimai, 1997.

Table 1. Yield of 10 cultivars under well-weeded conditions, Phimai, 1997.

Cultivar	Yield[a] (t ha^{-1})
IR66879-8-1-B	2.5 ab
IR69513-14-SRN-1-UBN-1-B	2.1 abc
IR46331-PMI-32-2-1-1	1.6 c
IR53466-B-118-B-B-20	1.8 bc
IR57514-PMI-5-B-1-2	2.5 a
Mahsuri	1.9 abc
RD6	1.8 bc
NSG19	0.9 d
RD23	1.8 bc
KDML105	2.3 abc

[a]Means followed by the same letter are not significantly different at $P = 0.05$.

There were significant differences in grain yield among 10 rice cultivars under fully weeded conditions (Table 1). IR57514-PMI-5-B-1-2, IR66879-8-1-B, KDML105, and IR69513-14-SRN-1-UBN-1-B produced high yield. NSG19 had the lowest grain yield because it was early maturing and was damaged by rats and birds during the booting to dough stage.

Cultivar flowering time greatly affected both weed number at maturity and percentage reduction in yield in the unweeded treatment. Thus, early flowering cultivars had more weeds at maturity than late-maturing cultivars; yield reduction was also greater among them. The same trend was observed under the partial weeding treatment, in which yield reduction varied from 0% to 43% among cultivars. Yield reduction in both unweeded and partially weeded treatments was related to weed number at harvest (Fig. 3). Cultivar competitiveness was closely related to weed number at harvest ($r = 0.64^{*}$), but not to the number at early growth stages.

Tapra. One mild drought occurred in late August at Tapra. Rice cultivars showed some leaf death and symptom of leaf rolling on 22 August, but the symptom did not differ significantly among cultivars. After heavy rainfall on 8 September, standing water remained in the field until harvest.

The majority of weed species at this experimental site were classified into three groups. Grassy weeds included *Digitaria adscendens* (H.B.K.) Henr., *D. sanguinalis* (L.) Scop., and *Echinochloa colona*. Sedges were *Fimbristylis miliacea*, *Cyperus pulcherimus* Wild. & Kunth, and *C. procerus* Rottb. Broadleaf weeds were *Ipomoea aquatica*, *Melochia corchorifolia* Linn., *Aeschynomene aspera* Linn., *Sesbania rostrata*, *Pentapetes phoenicea* Linn., *Crotalaria striata* DC, and *Ageratum conyzoides* L.

Weed weights differed significantly among 10 rice cultivars at 6 WAE. RD23 had the highest weed weight of 280 g m^{-2},whereas NSG19 had the lowest weed weight. Although weed weights measured at 2, 4, and 8 WAE were not significantly different among rice cultivars, they were similar to those at 6 WAE. Early flowering RD23 and KKNUR82003-SKN-69-1-1 had a higher weed weight than late-flowering KDML105.

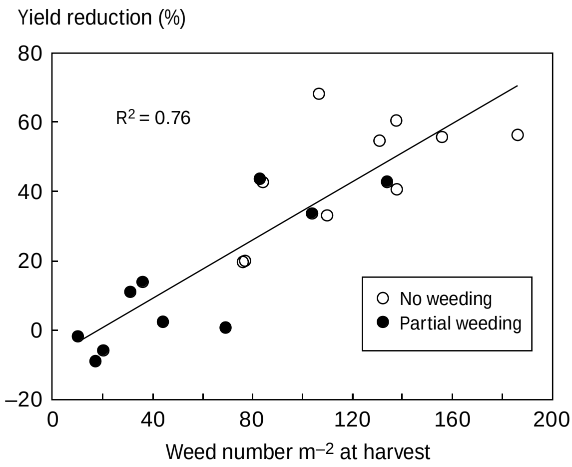

Fig. 3. Relationship between yield reduction (%) caused by weeds and weed number m^{-2} at harvest of 10 rice cultivars in two weeded conditions.

KKNUR82003-SKN-69-1-1 was a tall cultivar but was not competitive against weeds compared with other cultivars.

Grain yield was not significantly different between partially and fully weeded treatments, but it was significantly higher than that in the unweeded treatment. The mean grain yield of weeded treatments was 43% higher than that of unweeded crops. Grain yield reduction caused by weeds was 30% for KDML105, followed by RD6 (32%), whereas KKNUR82003-SKN-69-1-1 and RD23 had the highest percentage yield loss of 66% and 60%, respectively (Fig. 4). The percentage yield reduction generally decreased with a delay in flowering time. Yield in unweeded plots was directly related to maturity. Grain yield of rice cultivars with different weeding treatments was negatively related to weed weight at 6 WAE.

Seeding rate (1998)

Phimai. The dominant weed species were the same as those found in 1997. The importance of rice plant density for weed control and grain yield was demonstrated in this experiment. Without weed control, weed dry weight at 60 DAE increased with a decrease in rice seeding rate (Table 2). With an increase in seeding rate, established rice plant density and shoot dry matter increased, resulting in more complete suppression of weeds. The effect of seeding rate on rice plant dry matter was greater in the unweeded treatment than in the weeded treatment (data not shown).

Grain yield responded to seeding rate up to 200 kg ha^{-1} in the unweeded treatment (Table 3). When the crop was weeded, yield increased with a rise in rice seeding rate from 50 to 100 kg ha^{-1} but not beyond this level. Weed control increased yield

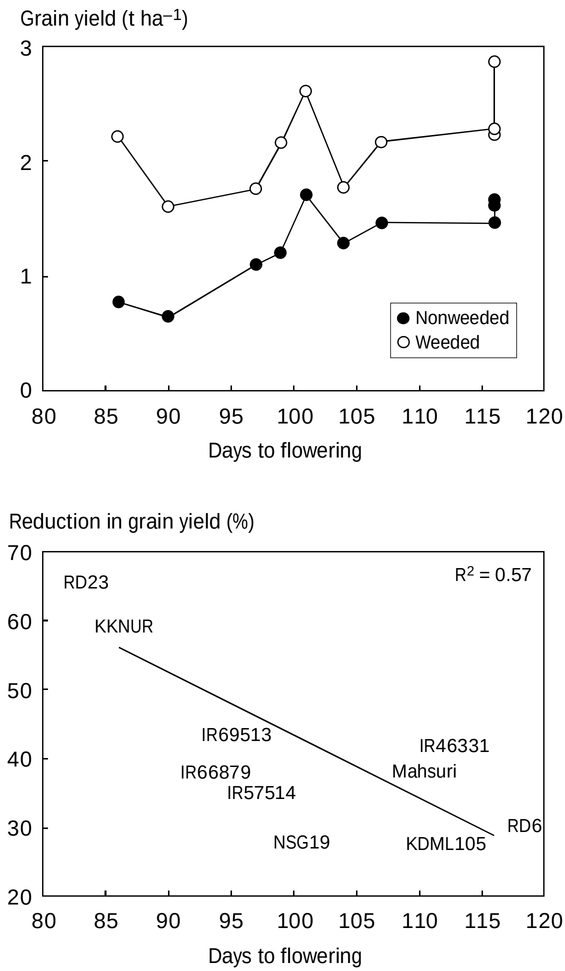

Fig. 4. Yield of 10 rice cultivars with or without weeding. Yield and yield reduction caused by weeds are shown in relation to flowering time, Tapra, 1997.

at any rice seeding rate but particularly under low seeding rates. Grain yield response to plant density was greater in RD23 than in KDML105, but the three-way interaction involving weed control treatments was not significant.

Tapra. Weed level in this experiment was lower than in the Phimai experiment and the effect of seeding rate was nil. There was, however, significant interaction effect between cultivar and weeding on grain yield (Table 4). The early maturing, short-statured cultivar RD23 was more affected by weeds than the late-maturing, taller cultivar KDML105.

Table 2. Effect of rice seeding rate and weed control on total weed dry weight at 60 days after rice emergence.

Seeding rate ($kg\ ha^{-1}$)	Weed dry weight[a] ($g\ m^{-2}$)	
	Without weeding	With weeding
50	294 a	37 a
100	162 bc	22 a
150	212 b	32 a
200	117 c	24 a
250	137 c	42 a
Mean	184	32

[a]Means followed by the same letter are not significantly different at $P = 0.05$.

Table 3. Effect of rice seeding rate and weed control on grain yield, Phimai, 1998.

Seeding rate ($kg\ ha^{-1}$)	Grain yield[a] ($t\ ha^{-1}$)	
	Without weeding	With weeding
50	0.9 c	2.4 b
100	1.3 bc	3.1 a
150	1.3 bc	2.6 ab
200	2.0 a	2.8 ab
250	1.6 ab	2.4 b
Mean	1.4	2.6

[a]Means followed by the same letter are not significantly different at the 5% level by Duncan's multiple range test.

Table 4. Mean yield ($t\ ha^{-1}$) of KDML105 and RD23 across five seeding rates under unweeded and well-weeded conditions, Tapra, 1998.

Cultivar	Unweeded[a]	Weeded
KDML105	2.1 a	2.3 b
RD23	1.8 a	2.7 a

[a]Cultivar yield means with the same letter are not significantly different at $P = 0.05$ within each treatment.

Discussion

Experiments have demonstrated the problems associated with early maturing cultivars. Smith (1986) also found that late-maturing cultivars were less affected by weed competition than early maturing cultivars. In this study, this may be associated with the fact that drought developed early in the season, which would have affected early flowering cultivars more severely (Fukai et al 1999). Late-maturing cultivars had more time to recover after the drought and they were able to compete against weeds more successfully than early maturing cultivars. This appeared to be particularly true in the 1997 Phimai cultivar experiment in which severe drought developed early in the season. Since both rice and weeds grew mostly in October toward the end of growth in this experiment, there was a negative relationship between weed number at maturity and rice yield in the Phimai cultivar experiment. In the Tapra cultivar experiment in 1997, where both rice and weeds would have grown well in September after early drought, there was a negative relationship between weed number during early growth stages and rice grain yield. Traditional, late-maturing tall rice cultivars with droopy leaves and vigorous tillering have advantages for competing against weeds. However, these advantages should be weighed against the likely yield loss caused by late-season drought (Jearakongman et al 1995). Potential yield is also not high in these traditional cultivars; thus, in high-yielding environments, with more favorable water availability and low weed populations, the medium-maturity and photoperiod-insensitive/mildly sensitive cultivars with higher yield potential would be advantageous.

Higher established plant density can also be achieved through increased seeding rate; this also reduces weeding time. If weed density is expected to be high, a seeding rate of 200 kg ha^{-1} would be required. Hand pulling of weeds in direct-seeded rice can be done two to three times from 2–3 wk after planting. This is usually sufficient to ensure optimum yield (Ampong-Nyarko and De Datta 1989). This was also found to be true in these experiments. To some extent, the choice of cultivar also affects established plant density. Cultivars with small seeds such as Mahsuri tend to have a higher established plant density. The condition of seed storage to maintain high germinability of seed is also important.

This study has shown that the direct seeding management option of cultivar selection—particularly maturity group, time of planting, and plant density—depends on growing conditions. It is therefore important to use available information at planting time to estimate the growing environment in terms of severity of weed problems and probability of drought development.

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Notes

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Research issues identified during the discussion sessions

This section provides a brief summary of research issues identified during group discussions and plenary sessions. The groupings for the issues listed below correspond to the discussion groups on the final day of the workshop.

Tillage, seed establishment, and weed control

- What is the effect of a nonrice crop on tillability/workability?
- Under what conditions can direct seeding of rice relax the constraints to crop intensification based on rice and nonrice crops?
- What is the benefit of immediate postharvest tillage in relation to weed control?
- What physical conditions favor zero-tillage/no-till seeding?
- What are the long-term effects of zero-tillage systems on the environment?
- What are the constraints to adopting row seeding?
- What are the benefits and costs (including environmental) of straw burning in relation to weed and pest control?
- Under what soil physical conditions does seed priming offer considerable benefits?
- What is the viability of broadcast primed seed with and without soil incorporation?
- How can we improve seed quality under farmers' conditions?
- What are seed quality problems under farmers' conditions? How can we improve farmers' awareness and knowledge regarding seed quality?
- What is the optimal timing for sowing in relation to rainfall (probability, risk analysis)?
- What is the role of soil compaction in improving emergence in dry-seeded rice?
- How are weed population dynamics affected by different weed control measures?

- How extensive is the use of herbicides for weed control? What are the potential environmental effects? What policies are needed to reduce the negative health and environmental effects of the indiscriminate use of herbicides?
- What are farmers' practices and their knowledge gaps regarding preemergence weed control in direct-seeded rice?

Nutrient and water management

- What is the best timing of N application in light-textured soils?
- What residue management strategies are needed for the sustainable enhancement of soil fertility?
- What are the differences in nutrient-use efficiency of direct-seeded and transplanted rice?
- What are optimal K/micronutrient management strategies for direct-seeded rice? How do green manure, farmyard manure, and upland crops contribute? What are the beneficial interactions with pests?
- What are the potential roles of livestock in nutrient cycling?
- What are farmers' practices in managing nutrients? What site-specific data on methods, source, timing, and rates of nutrient application are currently available for refining nutrient applications?
- What are the water-use efficiencies of dry-seeded, wet-seeded, and transplanted rice?
- What is the interaction between the timing of seeding and rainfall? Can it be better characterized based on GIS?
- What are the potential advantages/disadvantages of the following potential water-saving technologies:
  - Saturated field vs standing water
  - Use of early maturing varieties
  - Dry seeding vs transplanting in droughty areas
  - Role of dry seedling nursery and mulching
  - Management options to reduce percolation losses
  - Effect of direct seeding on water loss in different soil types

Germplasm improvement

- Can we develop improved germplam with shorter growth duration and higher yield potential under dry seeding?
- Can inter-/intraspecific crosses for weed competition and drought resistance be developed?
- What is the role of anoxia tolerance in direct-seeded rice?
- Under what conditions can hybrid rice be direct-seeded?
- What are the plant characteristics needed for dry seeding?

- What strategies are needed to expand the scope of a breeding program for the interaction between dry seeding and seedling vigor?
- What mechanisms govern the interaction between the method of seeding (such as depth and time of seeding) and seedling vigor?

Weed and insect management

- What are viable integrated crop management strategies for pest control in direct-seeded rice? What are the roles of environmentally friendly pesticides, biocontrol agents, and alternatives such as rotations, break crops, mulching, and tillage in different production systems?
- What are the effects of alternative weed management practices on long-term shifts in weed populations?
- How do weed management practices interact with nutrient/tillage practices?
- What are nonchemical methods for controlling snails?
- What are the opportunities for using weed-suppressing varieties?
- What is the incidence of sheath blight in direct-seeded rice and what are the management options?
- What are the likely effects of herbicide use on human health and the environment?

Systems-level issues

- We need to evaluate the effect of dry seeding at the cropping systems level not just for a single crop. The benefits (and costs) at the systems level may outweigh those for individual crops.
- More studies of farmers' practices and their knowledge and attitudes regarding various aspects of rice establishment are needed.
- Production systems that improve biodiversity and have a positive environmental effect need to be developed. The research focus should shift from that of the individual component to systems-level issues.
- Issues of scale from the field to the regional level need to be addressed to delineate the extrapolation domains for rice technologies.
- Economics and farmer acceptability of alternative technologies for crop establishment and management need to be evaluated in a farmer-participatory manner.