

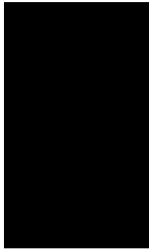


# Direct Seeded Flooded Rice in the Tropics

SELECTED PAPERS FROM THE  
International Rice Research Conference

**IRRI**

INTERNATIONAL RICE RESEARCH INSTITUTE



# Direct Seeded Flooded Rice in the Tropics

SELECTED PAPERS FROM THE  
International Rice Research Conference  
27–31 August 1990  
Seoul, Korea

CO-SPONSORED BY  
International Rice Research Institute  
Rural Development Administration, Korea

**1991**

International Rice Research Institute  
P.O. Box 933, 1099 Manila, Philippines

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# Foreword

The bulk of the world's rice supply comes from the irrigated ricelands. Recently, as labor for transplanting rice has become scarce and costs have risen, many irrigated and favorable rainfed rice farmers have been switching to direct seeding. With increased availability of short-duration modern rice varieties and cost-efficient herbicides, that trend is likely to continue—and accelerate.

One session of the 1990 International Rice Research Conference, cosponsored by IRRI and the Rural Development Administration of the Republic of Korea, focused specifically on direct seeding. Current practices and the potential for increasing and stabilizing yields in direct seeded flooded fields were discussed.

This book contains the research papers presented in that session and summarizes the discussion by participating scientists. Dr. B. S. Vergara was the technical editor; Dr. L. R. Pollard and Mrs. G. Argosino, the publication editors.

Klaus Lampe  
Director General

# Status and prospects of direct seeded flooded rice in tropical Asia

S. K. De Datta and P. Nantasomsaran

In recent years, increased irrigated areas, the availability of short-duration modern rices and cost-efficient herbicides, and high labor costs have motivated many farmers in Southeast Asia to shift from transplanting their flooded rice crops to broadcast seeding. In South Asia, particularly in Sri Lanka, broadcast seeded rice has traditionally covered large areas. Broadcast seeding has contributed to early establishment of the first crop and to increased rice crop intensification. The adoption of broadcast seeding onto puddled fields in irrigated, favorable rainfed, and unfavorable rainfed rice environments has been spectacular. But the switch to direct seeding has created new problems, such as major weed shifts. The agronomic requirements for successfully growing broadcast seeded flooded rice are being studied and documented by both national and international research programs. Rice varieties and cultural practices specifically adapted to direct seeding are needed, rather than relying on spillover benefits from using transplanted rice technology. Promising research findings and the development of cost-efficient and ecologically sound production technologies and rice varieties with higher yield potential will help make direct seeding an important production system in tropical Asia. The area under direct seeding in temperate climate rice-growing countries where transplanting has previously been the only system followed will also increase.

The availability of good water supplies through an expanded area under irrigation, relatively inexpensive herbicides, short-duration modern varieties, and increased labor costs have encouraged many farmers in Malaysia, the Philippines, Thailand, and other rice-growing countries in both tropical and temperate areas, to switch from transplanting to broadcast seeding their flooded rice crops (De Datta 1986, 1990). Concomitant changes that have favored this switch include the release of modern rice varieties with the high seedling vigor and tillering ability that increase the crop's ability to compete with weeds, and improved water control and increased availability of selective herbicides such as butachlor and thiobencarb that more effectively control weeds in broadcast seeded flooded rice (De Datta and Bemasor 1971, Moody and Cordova 1985).

Long-term trends in the Asian rice farmers' economic environment that also encourage the practice of direct seeding include declining real prices of rice and herbicides and increasing labor costs for transplanting and weeding (De Datta and Flinn 1986). Thus, adoption of broadcast seeded flooded rice culture is a rational response by rice farmers to a cost-price squeeze in rice production (Flinn and Mandac 1986).

In the Philippines, rice seed is broadcast onto puddled fields on at least 30% of the irrigated land in the dry season (De Datta 1986). In Central Luzon alone, where traditionally rice has been transplanted, adoption of broadcast seeding was rapid, from less than 2% of the rice area to 16% in 3 yr (1979-82) (Moody and Cordova 1985). Broadcast seeding on puddled soil has become popular in Camarines Sur. Mandac et al (1982) reported that the moisture status of a field and the introduction of more effective herbicides were causing the shift in crop establishment method. Lack of timely labor supply for hand weeding also encouraged the shift to broadcast seeding, as did availability of shorter duration rices with high yield potential (Abilay et al 1984). Recently, Erguiza et al (1990) reported that 86% of the farmers in Nueva Ecija Province, Philippines, used the transplanting method in 1979. Only 10% used direct seeding. By 1986 dry season, 27% had been forced to switch to broadcast seeding (Table 1). Those who in 1980 were practicing a combination of transplanting and wet seeding had, by 1986, shifted entirely to broadcast seeding.

In Malaysia, during the 1987 off-season, 99% of the planted area in the Muda irrigation scheme was direct seeded (Ho et al 1990). In Thailand, the broadcast seeded flooded rice area increased from 604,442 ha in 1985-86 to 645,308 ha in 1989-90, and an average grain yield increase from 3.9 to 4.3 t/ha during that period (Table 2). The area under broadcast seeded flooded rice in Thailand is higher in the dry season than in the wet season. As expected, dry season yields are higher by 0.25-0.54 t/ha.

**Table 1. Changes in crop establishment patterns of sample farms, Nueva Ecija, Philippines, 1979-80 and 1985-86 (Erguiza et al 1990).**

Crop establishment method <sup>a</sup>	1979 wet season to 1985 wet season		1980 dry season to 1986 dry season	
	no.	%	no.	%
WSR to TPR	1	nil	5	4
TPR to WSR	26	10	39	27
TPR to Mix	5	2	2	1
Mix to WSR	1	nil	6	4
Mix to TPR	1	nil	3	2
TPR to TPR	214	86	87	61
WSR to WSR	2	1	1	1
Mix to Mix		0	-	0
Total	250	100	143	100

<sup>a</sup> TPR =transplanting, WSR = wet seeding, Mix = combination of TPR and WSR.

**Table 2. Changes in area, production, and grain yield of broadcast seeded flooded rice in Thailand from 1985-86 to 1989-90 crop seasons. Source: P. Nantasomsaran, Agricultural Extension Department, Department of Agriculture, Thailand, 1990, pers. comm.**

	1985-86	1986-87	1987-88	1988-89	1989-90
Planted area (ha)	605,613	564,346	482,516	601,429	669,409
Harvested area (ha)	604,442	549,994	459,496	574,701	645,308
Production (t)	2,349,719	2,152,190	1,738,299	2,016,684	2,767,330
Grain yield (t/ha)	3.9	3.9	3.8	3.9	4.3

Broadcast seeded flooded rice culture is common in the central plain, western, and eastern parts of Thailand. The provinces that grow direct seeded rice are Pathum Thani, Chachongsao, Nakhon Pathom, and Suphan Buri.

Even in temperate climate countries such as Egypt and Korea, where transplanting has been the only system followed for a long time, farmers are switching to direct seeding.

Here we discuss the important developments that have occurred in direct seeded rice in tropical Asia and summarize current research thrusts, important research findings, and future prospects for direct seeding.

## Production technology and major research findings

Rice yield increases in tropical Asia have been attributed to the development of nonphotoperiod-sensitive, fertilizer-responsive, pest- and disease-resistant modern rice varieties, and to improved crop and resource management. Agricultural modernization brought about by the seed-water-fertilizer revolution has greatly modified many rice agroecosystems. Massive investments in irrigation infrastructure enabled rice production increase with only modest expansion of cultivable rice areas, predominantly through increased grain yield, but also through increased cropping intensity. In both favorable and unfavorable rainfed rice environments in the Philippines, moreover, adoption of broadcast seeding on puddled fields has been spectacular.

The agronomic package required to successfully grow broadcast seeded flooded rice is being researched.

## Varietal requirement

Currently, modern varieties that have been developed for transplanting are also used for broadcast seeding. These varieties often perform similarly, but sometimes give lower grain yields when broadcast seeded (Table 3). Dingkuhn et al (1990) summarize the basic plant type requirements for direct seeded flooded rice. Following are some examples of recent research findings on varietal evaluation.

**Table 3. Average yield of transplanted and broadcast seeded flooded rice in continuous cropping experiments at IRRI, 1968-90.**

Planting season	Yield (t/ha)	
	Transplanted	Broadcast seeded flooded
	<i>Average of 92 varieties and 4 N levels</i>	
Dry	5.2	5.1
Early wet	3.8	3.8
Late wet	3.2	3.0
	<i>Average of 66 crops using 386 varieties</i>	
	4.1	4.1

In a field experiment at IRRI, agronomic traits of modern rices IR36, IR42, IR58, IR64, IR29723-143-3-2-1, and IR32429-47-3-2-2 were evaluated under broadcast seeding and transplanting with 0, 75, and 150 kg N/ha. Without fertilizer N, broadcast seeded rice produced more tillers per unit area than did transplanted rice. As N level increased to 75 kg N/ha, tiller number per unit area remained similar for both systems. At low N, when short-duration IR36, IR58, IR64, and IR3242-47-3-2-2 were broadcast seeded, grain yields were as high as or better than when they were transplanted. Medium-statured, medium- to long-duration IR42 and IR29723-143-3-2-1 generally had higher yields when transplanted than when broadcast seeded (Cia 1986).

Yield losses due to lodging have been reported to reach as high as 1 t/ha, even in some modern varieties (IRRI 1985). Recent research suggests that transplanted rice is more flexible, with greater lodging resistance than broadcast seeded rice (Table 4). Rice culm thickness and rooting behavior were probably responsible for that greater lodging resistance.

**Table 4. Elasticity index of transplanted and broadcast seeded flooded rices at harvest as affected by N rate. IRRI, 1986 dry season (Cia 1990).**

Crop establishment	Elasticity index <sup>a</sup>					
	IR36	IR42	IR58	IR64	IR29723-143-3-2-1	IR32429-47-3-2-2
	<i>No nitrogen</i>					
Transplanted	0.83 a	0.86 a	0.83 a	0.86 a	0.83 a	0.83 a
Broadcast	0.58 b	0.72 b	0.61 b	0.54 b	0.65 b	0.49 b
	<i>75 kg N/ha</i>					
Transplanted	0.69 a	0.80 a	0.78 a	0.86 a	0.75 a	0.75 a
Broadcast	0.62 a	0.66 b	0.54 b	0.58 b	0.75 a	0.55 b
	<i>150 kg N/ha</i>					
Transplanted	0.63 a	0.50 a	0.68 a	0.78 a	0.20 a	0.67 a
Broadcast	0.53 b	0.44 a	0.47 b	0.53 b	0.21 a	0.44 b

<sup>a</sup>At the same N rate in a column, means followed by a common letter are not significantly different at the 5% level by DMRT.

In an experiment at IRRI, semidwarf modern varieties such as IR68 and IR72 grown under broadcast seeded flooded rice culture did not differ from transplanted rice in weed biomass and grain yield (Fig. 1).

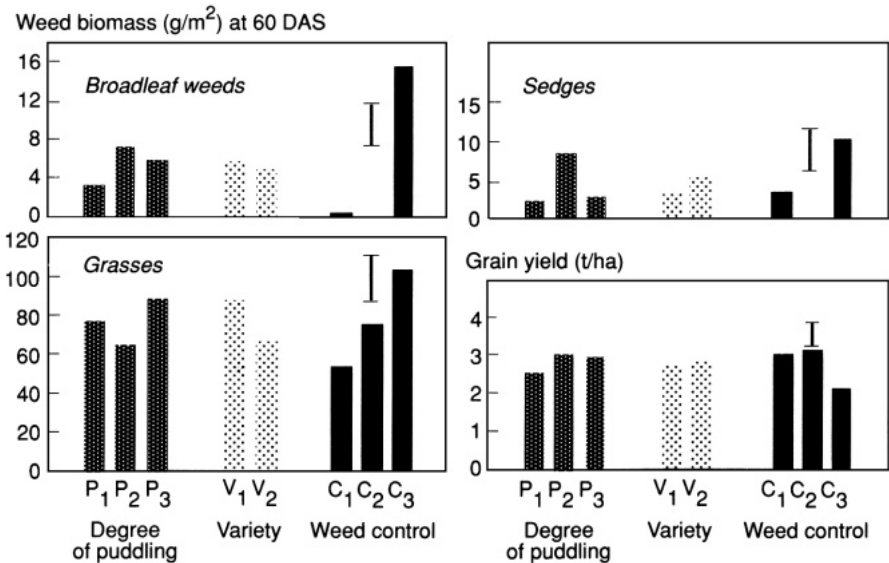
### Land preparation

Land preparation for broadcast seeding is essentially similar to that for transplanting (Moody 1977). However, better field leveling is necessary for broadcast seeding, to achieve good water control and crop establishment and avoid poor seedling germination and poor root anchorage where the water is too deep (De Datta 1986). IRRI research shows that 100 kg pregerminated rice seed/ha (subjected to 24 h soaking and 48 h incubation) gives the best stand establishment and weed control.

In a recent experiment at IRRI (Nabheerong 1990), weed biomass and grain yields were not significantly affected by the degree of puddling. Chemical weed control significantly reduced weed biomass and increased grain yield (Fig. 1).

### Weed shift and management

Direct seeded rice culture has aggravated weed problems. Occurrence of *Echinochloa* spp. (barnyard grass) increased in Malaysia's major rice granary areas after the introduction of direct seeding (Baki 1982). Hierarchical dominance in the Muda area was in the order of *Fimbristylis miliacea* (L.) Vahl > *Monochoria vaginalis* (Burm. f.)



1. Weed biomass at 60 days after sowing (DAS) as affected by degree of puddling, rice cultivar, and weed control method in broadcast seeded flooded rice. IRRI, 1989 WS. P<sub>1</sub> = 1 plowing + 1 harrowing, P<sub>2</sub> = 1 plowing + 2 harrowings, P<sub>3</sub> = 1 plowing + 3 harrowings. V<sub>1</sub> = IR68, V<sub>2</sub> = IR72. Bar = LSD 0.05. C<sub>1</sub> = bensulfuron, C<sub>2</sub> = butachlor + bensulfuron, C<sub>3</sub> = untreated control.

Presl > *Echinochloa crus-galli* Beauv. ssp. *hispidula* (Retz.) Honda > *Scirpus grossus* L.f. > *Marsilea minuta* L. (Syn. *M. crenata* Presl) (Ho and Md Zuki 1988).

Subsequent surveys in the Muda area in 1987 and 1988 revealed that when direct seeding was practiced on 65-99% of the planted area, grasses became predominant (Ho and Md Zuki 1989). The order of severity was *E. crus-galli*/*E. colona* L. Link > *F. miliacea* > *Leptochloa chinensis* (L.) Nees > *M. minuta* > *Sphenoclea zeylanica* Gaertn. > *Scirpus grossus*. *E. crus-galli* and *E. colona* were the most noxious. Together, these two weeds inflicted severe yield loss on 10,178 ha, 11% of the total rice area (Ho and Md Zuki 1988). To redress the grassy weed problems, the Muda Agricultural Development Authority (MADA) launched a strategic extension campaign (SEC) during 1989 off-season that followed an integrated weed management concept (Ho et al 1990). The steps involved are

1. Using two rounds of dry rototilling and land leveling.
2. Using weed-free, clean seeds.
3. Filling vacant areas in the field with healthy seedlings.
4. Applying direct weed control measures, using herbicides and hand weeding.
5. Closely adhering to irrigation schedules.

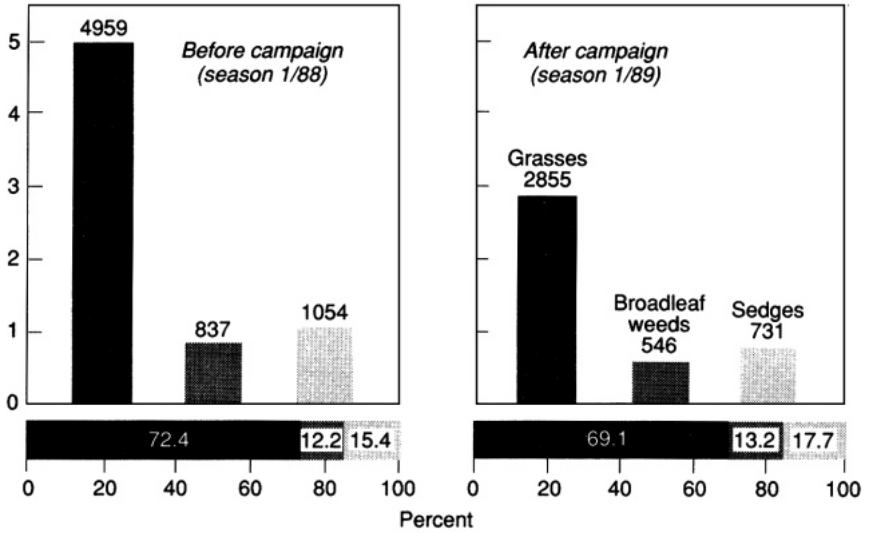
By following these stringent steps, *Echinochloa* spp. infestation was drastically reduced during the 1-yr study (1986-87) (Ho et al 1990). Furthermore, average grain yields increased from 3.4 to 4 t/ha (Ho et al 1987).

The success of the project gave MADA the necessary assurance to adopt this simplified technology for an Integrated Weed Management (IWM) campaign in the 1988-89 cropping seasons. Weed surveys, based on a rapid appraisal approach that assessed the impact of IWM on weed population changes over the entire Muda area, showed that IWM significantly minimized weed infestation in the campaign area. The surveys were conducted at the peak period of weed flowering.

Although grasses remained the predominant group, their dominance had declined (Fig. 2). *E. crus-galli*/*E. colona*, the principal grassy weeds found during the campaign, were effectively controlled. An Information Recall and Impact Survey (IRIS) conducted after the campaign showed that the remarkably reduced grass population was due to the steps stipulated earlier (Khor and Ramli 1990). Use of the herbicide propanil increased from 4.8 to 16.7% and propanil + molinate mixture from 5.3 to 19.3%. While *E. crus-galli*/*E. colona* populations decreased, infestation of *L. chinensis* and *Ischaemum rugosum* Salisb. escalated, by 52 and 870%, respectively (Fig. 3). In those fields, molinate used for two consecutive seasons selectively controlled barnyard grass, leaving other grasses uncontrolled. These results confirm the earlier report (Bemasor and De Datta 1988) that continuous use of the same or similar herbicides leads to undesirable weed shifts.

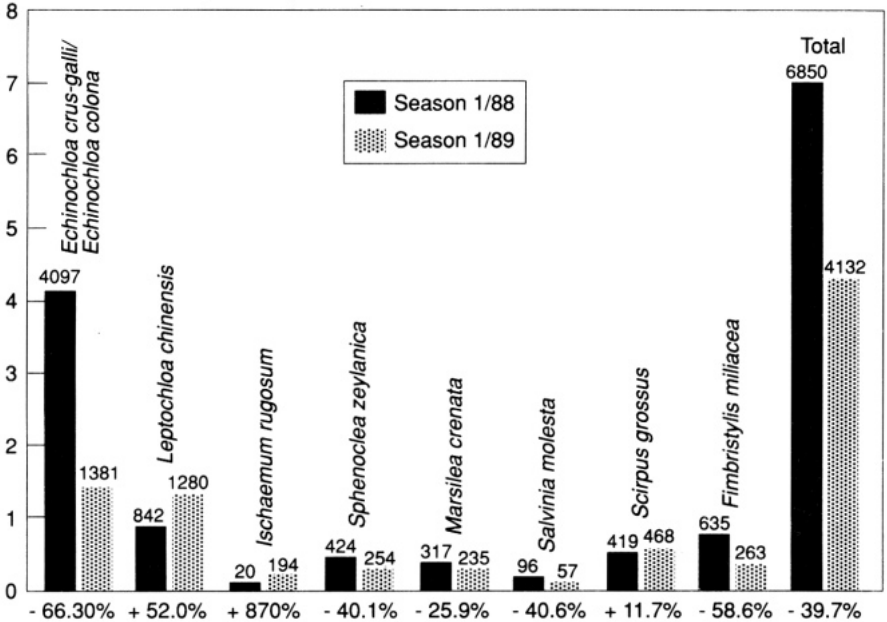
After evaluating the effects on grain yield of barnyard grass *E. crus-galli* and rice bug *Leptocoris oratorius*, both widespread pests in Peninsular Malaysia, Supad et al (1989) noted that *L. oratorius* reduces grain yield through interference during spikelet filling. Damage was significantly greater in weed-free plots than in plots with *E. crus-*

Weed-infested area (x1000 ha)



2. Major weed infestation before and after a strategic extension campaign in Malaysia (adapted from Ho et al 1990).

Weed-infested area (x1000 ha)

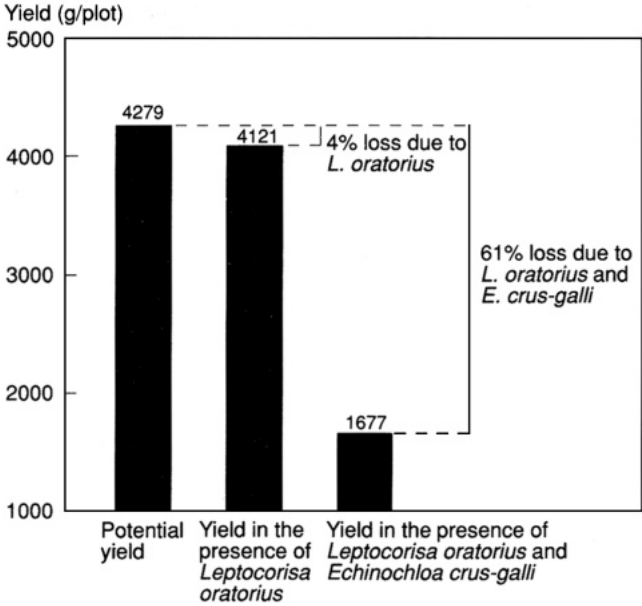


3. Weed group profile in campaign area of Malaysia, expressed in weed hectare and proportion of total infestation (adapted from Ho et al 1990).

*galli*. The interaction effects between weed and insect on grain yields were not significant. In weed-free plots, grain damage caused by *L. oratorius* was about 4%, on the basis of weight. On the other hand, yield from plots where effects of both weed and insect were combined was reduced by about 61% (Fig. 4).

In Thailand, herbicide use is not as high as it is in Malaysia, and widespread shifts of weed species have not occurred. In the central plains, however, most ricefields are infested with *E. crus-galli*. Other weeds present are *S. zeylanica*, *M. vaginalis*, *Cyperus difformis* L., and *M. crenata*. Research results at Chainat suggest that, of the many herbicides tested, thiobencarb and bensulfuron-methyl performed best (Vongsaroj et al 1987). Butachlor/2,4-D and oxadiazon 2,4-D were toxic to rice.

When herbicides were used continuously in the Philippines, control of annual weeds such as *M. vaginalis* and *Echinochloa* spp. and perennial weeds such as *Scirpus maritimus* L., *Paspalum distichum* L., and *Pistia stratiotes* L. became a difficult problem (De Datta 1977). The amount of herbicides applied to broadcast seeded rice and transplanted rice differed significantly. Farmers who used broadcast seeding relied more heavily on chemicals to control weeds than did farmers who transplanted. Herbicides alone were used by 71% of the broadcast seeding farmers and 52% of the transplanting farmers. The rest used manual weeding, a combination of hand weeding and chemicals, or no weed control (Table 5).



4. Effect of *Echinochloa crus-galli* and *Leptocorisa oratorius* on yield of direct seeded rice (adapted from Supad et al 1989).

**Table 5. Weed control practices by crop establishment method, Nueva Ecija, Philippines, 1986 dry season (adapted from Erguiza et al 1990).**

Weed control method	Transplanted		Broadcast seeded flooded	
	Farms (no.)	%	Farms (no.)	%
Manual only	9	8	0	0
Chemical only	57	52	44	71
Combination of manual and chemical	37	34	17	27
None	7	6	1	2
Total	110	100	62	100

### Fertilizer nitrogen management

With any rice establishment method, N fertilization is one of the important factors that affect rice production (Mikkelsen 1987). N accounts for about 67% of the total amount of fertilizers applied to rice. Management practices for basal fertilizer N application are similar for both transplanting and broadcast seeding. Many Philippine farmers broadcast the first dose of fertilizer 2-3 wk after broadcasting pregerminated seeds, a practice similar to that followed for transplanted rice.

An IRRI survey suggests that in Nueva Ecija Province, the total amount of fertilizer applied was higher for transplanted than for broadcast seeded rice, although the mean difference was not significant (Erguiza et al 1990). In effect, less fertilizer was applied to broadcast seeded rice. That may be a rational decision, since high fertilizer N application increases lodging, particularly in a broadcast seeded crop with poor root establishment (Cia 1986).

With the increasing popularity of broadcast seeding in Southeast Asia, it is imperative that efficient fertilizer management practices be developed. Knowledge of N transformation pathways is vital to the design of management practices that will lead to efficient N use.

Recently, De Datta et al (1988) evaluated broadcast seeded and transplanted rice under similar N management practices. With applied urea, mean <sup>15</sup>N plant recovery was greater for broadcast seeded rice (47%) than for transplanted rice (37%). Transplanted rice produced 10 kg more grain/kg applied N than did broadcast seeded rice, in part because without applied N, mean grain yield of transplanted rice was 0.3 t/ha lower than that of broadcast seeded rice. These results suggest considerable potential to increase N use efficiency and grain yield in broadcast seeded rice by manipulating N fertilizer and water management practices.

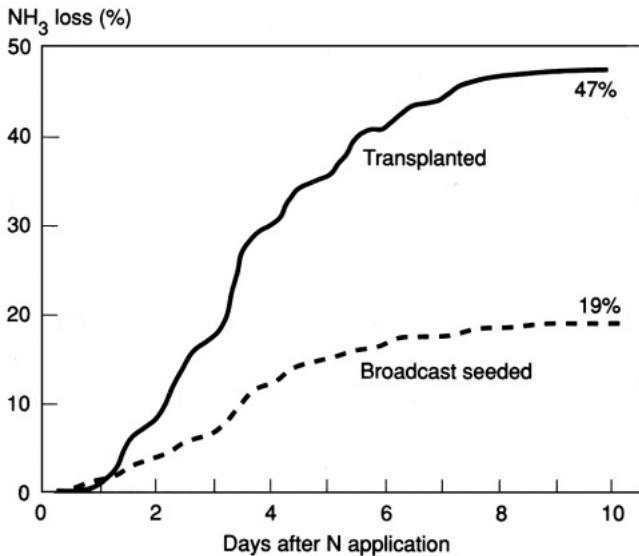
An experiment in 1989 evaluated ammonia (NH<sub>3</sub>) volatilization (using micrometeorological techniques and total N losses (using <sup>15</sup>N balance method) in farmers' fields in Calauan, Laguna, Philippines (De Datta et al 1989a). Relative N losses in broadcast seeded flooded rice were directly compared with those in transplanted rice. Results suggest that by switching from transplanting to broadcast seeding, NH<sub>3</sub> volatilization loss can be reduced by 28% of the total N applied, even with farmers' current fertilizer

N management practices (Fig. 5). The data indicate that by broadcast seeding rice, farmers can reduce total N loss by 9-10% of the total N applied, even if they are reluctant to change their current fertilizer N management practices. Ten percent of the entire urea applied to rice in Asia is valued at approximately US\$450 million (Obcemea et al 1990).

In a recent experiment on N transformation in transplanted and direct seeded flooded rice at the Philippine Rice Research Institute farm in Maligaya (Diekmann 1990), depletion of exchangeable  $\text{NH}_4^+$ -N was attributed primarily to plant N uptake. Exchangeable  $\text{NH}_4^+$ -N depletion was faster in direct seeded rice, presumably because of its higher growth rate during the vegetative stage and its more rapid N uptake. Because transplanted rice suffered from transplanting shock, its plant N uptake was lower than that of direct seeded rice during the first 20 d after fertilizer application, delaying exchangeable  $\text{NH}_4^+$ -N depletion by plant absorption (Diekmann 1990).

Incorporation of *Sesbania rostrata* and *Aeschynomene afraspera* green manure and urea N significantly increased grain yield in both direct seeded and transplanted rice, compared with no fertilizer N (Table 6). During the dry season, grain yields were slightly but significantly higher in transplanted than in direct seeded rice.

A significant finding was root dry weight, which was higher for direct seeded than for transplanted rice (Fig. 6). In direct seeded rice, root dry weight reached its maximum about 70 d after seeding, then declined. In transplanted rice, root dry weight reached its maximum during crop maturity.



5. Quantification of ammonia ( $\text{NH}_3$ ) volatilization losses by micrometeorological technique under broadcast seeded and transplanted flooded rice culture. Farmers' fields, Calauan, Laguna, Philippines, 1989 dry season (adapted from De Datta et al 1989a).

**Table 6. Grain yield of transplanted and broadcast seeded flooded IR64 rice as affected by N source. Maligaya Rice Research and Training Center, Nueva Ecija, Philippines, 1978 (adapted from Diekmann 1990).**

N source	Grain yield (t/ha)			
	Dry season		Wet season	
	Transplanted	Broadcast seeded	Transplanted	Broadcast seeded
<i>Sesbania rostrata</i>	8.2	7.7	5.4	4.5
<i>S. rostrata</i> <sup>a</sup>	8.4	8.0	5.2	4.6
<i>Aeschynomene</i>	7.4	7.4	5.3	4.3
<i>A. afraspera</i> <sup>a</sup>				
<i>A. afraspera</i> <sup>b</sup>	7.5	7.6	5.2	4.4
Urea	8.6	8.1	5.1	4.1
No fertilizer N	5.2	4.3	3.5	2.8
LSD (0.05)	0.5		0.5	

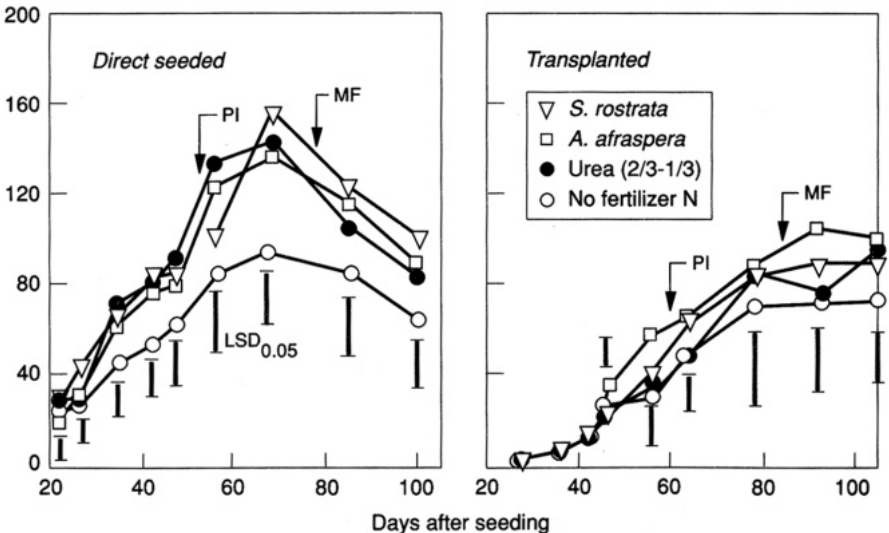
<sup>a</sup>All of *S. rostrata* and *A. afraspera* green manure basally applied; urea applied in 2/3-1/3 split.

<sup>b</sup>2/3 N basally applied as green manure + 1/3 N as urea topdressed 5-7 d before panicle initiation.

### Economics of broadcast seeding onto puddled fields

Broadcast seeding onto puddled fields, with its reduced crop establishment costs, is a low-cost alternative to transplanting. Erguiza et al (1990) suggested that a decline in the real price of rice, if other prices are held constant, will encourage farmers to adopt

#### Root dry wt (g/m<sup>2</sup>)



6. Root dry weight at various growth stages of direct seeded and transplanted IR64 as affected by N source. Philippine Rice Research and Training Institute, Maligaya, Nueva Ecija, Philippines, 1988 dry season. PI = panicle initiation, MF = maximum flowering (Cia 1986).

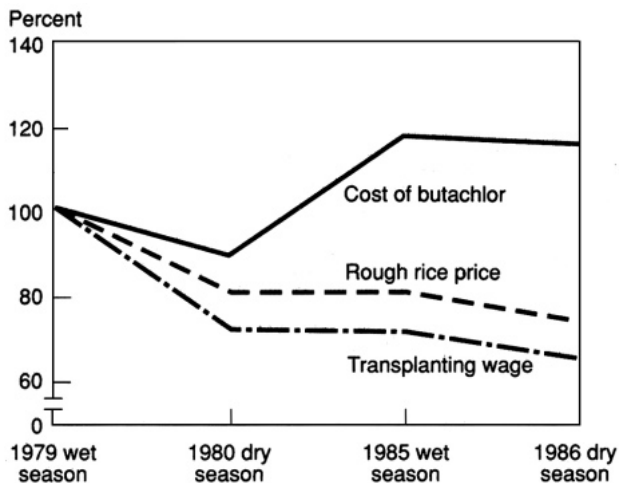
cost-saving innovations to sustain farm profits. The economics of broadcast seeding onto puddled fields or onto dry soil, however, varies greatly in Southeast Asia.

The Philippine experience shows that considerably less labor is needed in broadcast seeded flooded rice than in transplanted rice, mainly because of savings in crop establishment (Coxhead 1984). On the other hand, land preparation and water control costs are higher for broadcast seeded than for transplanted rice (De Datta and Ampong-Nyarko 1988). The net effect favors direct seeded rice.

The primary difference between broadcast seeding and transplanting is the amount of labor used for crop establishment (De Datta 1986, De Datta and Flinn 1986). In a recent study, Erguiza et al (1990) found that total paid-out costs were 16% higher for transplanted rice, largely because of the high cost of hired labor for crop establishment. Transplanted farms in Nueva Ecija Province spent US\$28/ha for crop establishment; broadcast seeded flooded rice farms spent US\$1/ha. Both the price of rice and the transplanting wage rate declined in Central Luzon, while the price of herbicides increased between 1979 and 1986 (Fig. 7).

In Malaysia, imputed labor cost for direct seeding was only US\$15/ha, compared with US\$37/ha for transplanting (De Datta et al 1989b).

In Thailand, herbicide use became widespread because of the high labor cost of hand weeding, which increased 15% within 5 yr, from US\$1/man-day in 1978 to US\$2.50 in 1983. The current rate is US\$3.50/d. However, the shift to herbicides has not been as fast as the increase in wages because of farmers' low acceptance of chemical weed control and lack of knowledge in herbicide use (Suwunnamek 1983). Total production cost for broadcast seeded flooded rice is lower than that for transplanted rice, and slightly higher for transplanted photoperiod-insensitive varieties (Table 7) than for photoperiod-sensitive varieties (Table 8).



7. Real wage and price indices by season. Nueva Ecija, Philippines. 1979-80 and 1985-86 (Erguiza et al 1990).

**Table 7. Production cost of photoperiod-insensitive varieties in broadcast seeded and transplanted flooded rice in Thailand. <sup>a</sup>**

Year	Location	Variety <sup>b</sup>	Production cost (\$/ha)		Cost (\$/t)	
			Broadcast seeded	Transplanted	Broadcast seeded	Transplanted
1984	7	3	298	344	79	91
1985	10	2	340	361	100	104
1986	18	5	357	378	95	110

<sup>a</sup> Data collected by P. Nantasomsaran, Department of Agriculture, Thailand. <sup>b</sup> Varieties RD1, RD7, RD10, RD21, RD23, and RD25.

**Table 8. Production cost of photoperiod-sensitive varieties in broadcast seeded and transplanted flooded rice in Thailand. <sup>a</sup>**

Year	Location	Variety <sup>b</sup>	Production cost (\$/ha)		Cost (\$/t)	
			Broadcast seeded	Transplanted	Broadcast seeded	Transplanted
1984	7	5	269	316	74	84
1985	12	7	340	361	114	122
1986	18	8	347	383	110	121

<sup>a</sup> Data collected by P. Nantasomsaran, Department of Agriculture, Thailand. <sup>b</sup> Varieties Khao Ta Hang 17, Leungpratew 123, Khao Dhok Mali 105, RD6, RD13, RD27, Nam Sagui 19, Kaenchan, Sanpathong, Leb Mue Nahng 111.

In the Philippines, detailed studies (Erguiza et al 1990) suggest that an upward trend in transplanting costs encourages farmers to adopt a labor-saving crop establishment method. Farmers with low credit requirements, however, are more likely to transplant. Other studies note that women in rice farming are more disadvantaged by a switch to direct seeding because of their greater involvement in transplanting activities (Moody and Cordova 1985).

## Prospects of direct seeded flooded rice

The recent widespread adoption of broadcast seeded flooded rice culture has been attributed to a range of biophysical and socioeconomic factors, and farmers in Southeast Asia are expected to continue to substitute capital (in the form of seed and herbicides) for labor. The analysis by Erguiza et al (1990) suggests that the labor cost advantage of direct seeding more than compensates for the increase in herbicide cost. Furthermore, the probability of adoption of broadcast seeding, or at least some form of direct seeding, is expected to be greater in the future, despite increasing herbicide costs and the current and projected trend of a decline in the real price of rice. On the other hand, increases in fertilizer prices may discourage farmers from adopting direct

seeding. The finding (De Datta et al 1989a) that broadcast seeding onto puddled fields can reduce  $\text{NH}_3$  volatilization loss by 28% and total N losses by 10% will further support the switch to broadcast seeding. Even more N savings are possible by growing green manure crops such as *Sesbania rostrata* and *Aeschynomene afraspera* as a part or complete substitute for inorganic N fertilizers (Diekmann 1990).

In Malaysia, direct seeding onto puddled fields or by dry drill seeding is common in areas under the Muda irrigation scheme, where major production problems associated with direct seeding are handled by intensive extension and training programs (Ho et al 1990).

In Thailand, which has undergone rapid industrialization, labor costs have increased steadily and farm labor is scarce. In some irrigated areas, particularly in Pathum Thani, Chachongsao, Nakhon Pathom, and Suphan Buri Provinces, direct seeding is practiced extensively. With improved technology, most farmers in the central plains and other areas probably will eventually adopt direct seeding.

In the Philippines, women are more disadvantaged than men because of their greater participation in transplanting activities (Moody and Cordova 1985, Erguiza et al 1990). This means that alternative income-generating activities should be developed for women in the farming community. Among possible farming systems alternatives are a rice - fish cropping, mushroom production using rice straw, and market-oriented vegetable production in sequence with rice.

Research prospects for direct seeded rice culture are highly promising. There is an increased awareness among plant breeders of the need to develop germplasm specific to direct seeding. Some progress has been made in conceptualizing a plant type for direct seeded flooded rice culture (Dingkuhn et al 1990).

Based on current trends in research results, we believe that the next major breakthrough in raising the yield potential of irrigated rice from the current 10-11 to 13-15 t/ha may come from direct seeded rice rather than from transplanted rice.

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## Notes

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Concepts for a new plant type for direct seeded flooded tropical rice

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Direct seeded flooded rice is gradually replacing transplanted rice in many rice-growing areas of the tropics. Current high-yielding cultivars were bred for transplanted rice culture; little is known about the yield potential and plant type requirements for direct seeded flooded rice. Several field experiments in the Philippines were used to analyze the growth characteristics and yield potential of semidwarf IR rices when direct seeded. Simulation aided data interpretation and generated concepts for plant types with improved yield potential. Compared with transplanted rice, the same varieties when direct seeded required greater N inputs to produce the same yield. The absence of transplanting shock and a dense plant population caused excessive leaf and tiller production, followed by N dilution and premature senescence through foliar N deficiency. Maximum grain yields were 9 t/ha. Simulation indicated that yield potential can theoretically be increased 25% through modified assimilate partitioning between leaves and stems and by enhancing the vertical N concentration gradient within the foliage. Even greater yield improvements are predicted for plant types with a prolonged ripening period and sustained high foliar N concentrations. Components of a new plant type concept for greater resource use efficiency and yield potential include a) enhanced foliar growth during crop establishment, in combination with reduced tillering; b) less foliar growth and enhanced assimilate export from leaves to stems during late vegetative and reproductive growth, along with sustained high foliar N concentration; c) a steeper slope of the vertical N concentration gradient in the leaf canopy, with more N present in the uppermost stratum; d) expanded capacity of stems to store assimilates; and e) improved reproductive sink capacity, with a prolonged ripening period.

For centuries, in many regions of Asia, flooded rice has been understood as almost synonymous with transplanted rice. Now the availability of improved weed control technologies; the development of new, fast-establishing, early-maturing rices; and rising prices for labor in some rural rice-growing areas are motivating many farmers to shift from transplanting to direct seeding (De Datta 1986, Erguiza et al 1990).

Virtually all modern, high-yielding tropical lowland rice cultivars, however, were selected and bred for transplanted rice culture. Until recently, little information existed on how these cultivars performed when seeded directly and grown in dense populations, as is the case in broadcast seeded rice culture (the most popular direct seeding practice among farmers).

Studies using semidwarf IR cultivars indicate that direct seeded flooded rice culture results in crop growth dynamics profoundly different from those resulting from transplanted rice culture (Dingkuhn et al 1990 a,b,c; Schnier et al 1990a,b). Early production of a large vegetative biomass, leaf area, and tiller number is characteristic of direct seeded flooded rice.

Its greater vegetative growth, compared with that of transplanted rice, is only partly due to a denser plant population, and thus more light interception during crop establishment. An equally important factor is the absence of transplanting shock, with a consequent absence of an initial lag-phase of growth (Dingkuhn et al 1990c). The resulting abundance of vegetative biomass impedes the yield formation process through nitrogen dilution and high maintenance respiration (Dingkuhn et al 1990a).

The design of new, high-yielding, resource use-efficient cultivars for direct seeded rice culture requires new knowledge on how the biological growth potential of rice can be translated into improved yields. Modern high-yielding rices have attained a yield plateau that is proving difficult to surmount using current plant types (Akita 1989, Tanaka et al 1966).

In the study reported here, we compared the growth dynamics and yield components of transplanted and direct seeded flooded rice as measured in field observations. Simulation helped explain the crop dynamics observed and generated predictions on how modified plant types would perform in a range of nutritional environments. The objective was to identify and quantify changes in plant characteristics that would raise the grain yield potential of direct seeded flooded rice at given N input levels, and of tropical irrigated rice in general.

## Materials and methods

Improved, lowland-adapted, semidwarf indica rices IR58, IR64, IR72, and IR29723 were grown in various field experiments during the 1986, 1987, 1988, and 1989 dry seasons (January-May) in two locations in the Philippines. One site was the IRRI experimental farm at Los Baños, Laguna; the other, the Maligaya Rice Research and Training Center (MRRTC) farm in Muñoz, Nueva Ecija.

All experiments used different plant establishment practices and sequential observations of plant dry matter accumulation (DM), N uptake and its distribution within the plant, leaf area index (LAI), tiller number, tissue death, and canopy CO<sub>2</sub> exchange rate (CER) throughout the growing seasons. The crops were transplanted using 20-d-old seedlings or direct seeded using pregerminated seed. Direct seeding treatments were broadcast seeding, dibble seeding at the same planting density and geometry as in transplanted, row seeding, or broadcast seeding with subsequent introduction of rows.

Treatments were laid out in factorial randomized complete block designs with four replications (experiment 1 had three replications).

Population densities averaged 100 (transplanted and dibble-seeded rice), 180 (row seeded), and 250 (broadcast seeded) plants/m<sup>2</sup>, with 4 plants/hill in transplanted and dibble-seeded rice. Spacing was 0.2 m between hills in transplanted and dibble-seeded rice and 0.25 m between rows in row seeded rice. Plots were kept flooded at 0.05 m water depth to 2 wk before maturity, then drained and allowed to dry.

CER was measured with a nondestructive, mobile, depletion system that enclosed a 0.6- × 0.6-m field area for less than 1 min per measurement. Gas exchange of single leaves was measured porometrically using an open system. (For details of the gas exchange measurement techniques, see Dingkuhn et al 1990c for canopy-based observations and Dingkuhn et al 1990e for leaf-level observations.) Sequential destructive sampling in each plot for leaf area, DM, N content, and tiller number was based on a 0.6- × 0.4-m area during vegetative growth and on a 0.4- × 0.4-m area during reproductive growth. Yield at maturity was determined from a 7.2-m<sup>2</sup> area. Plants from two hills or an equivalent ground area were collected from each corner of the yield sample area, for a combined sample of 0.32-m<sup>2</sup>/plot to determine yield components.

The experiments conducted were the following (for further details, see the references cited):

- Experiment 1: 1986 dry season, IRRI site, IR64 rice (Dingkuhn et al 1990c); crop establishment by transplanting and dibble seeding. Whole-season dynamics of DM, N uptake, LAI, tiller number, and CER. Diurnal observations on CER and evapotranspiration and response of CER to light.
- Experiment 2: 1986 dry season, IRRI site, IR64 rice; crop establishment by transplanting; different N rates and timing (Ingram et al 1990). Whole-season dynamics of DM, N uptake, LAI, tiller number, CER, and diurnal patterns of CER.
- Experiment 3: 1987 dry season, MRRTC site, IR64 rice; crop establishment by transplanting, dibble seeding, row seeding, and broadcast; different N rates, methods, and timing (Schnier et al 1990b). Whole-season dynamics of DM, N uptake, LAI, tiller number, CER, and diurnal patterns of CER.
- Experiment 4: 1988 dry season, MRRTC site, IR64 rice; crop establishment by transplanting and row seeding; 0, 30, 60, 90, 120, 150 kg N/ha (Schnier et al 1990a, Dingkuhn et al 1990a). Whole-season dynamics of DM, N uptake, LAI, tiller number, tiller death, and CER. Fertilizer N was applied using the liquid band placement technique (Schnier et al 1988); that suppressed N volatilization losses and made applied N almost quantitatively available to the plant.
- Experiment 5: 1988 dry season, MRRTC site, IR58, IR64, and IR27923 rice; crop establishment by transplanting, broadcast and broadcast with rows; different rates and timing of N (Dingkuhn et al 1990b). Whole-season dynamics of DM, N uptake, LAI, tiller number, tiller death, and CER.
- Experiment 6: 1989 dry season, MRRTC site, IR72 rice; crop establishment by transplanting, dibble seeding, and broadcast; different rates and timing of N (Dingkuhn et al 1990d,e). Whole-season dynamics of DM, N uptake, LAI, tiller

number, tiller death, and CER, with emphasis on the flowering stage. Study of canopy stratification. Single-leaf gas exchange measurements at flowering.

For the simulation research, we developed a crop growth model L3QT. Its name reflects the fact that it simulates growth under N shortage (i.e., crop production level 3, de Wit 1986) with quarter-day integration intervals, and that it includes tiller formation. The major part of this model (L1Q + TIL described by Penning de Vries et al 1989) simulates processes of photosynthesis, respiration, partitioning, and phenological development from early establishment to maturity, and distinguishes among leaves (blades), stems, roots, panicles, and tiller number. L3QT accounts for changes in weather that occur continuously, particularly changes in solar radiation and temperature. As much as possible, these processes are described at a physiological level.

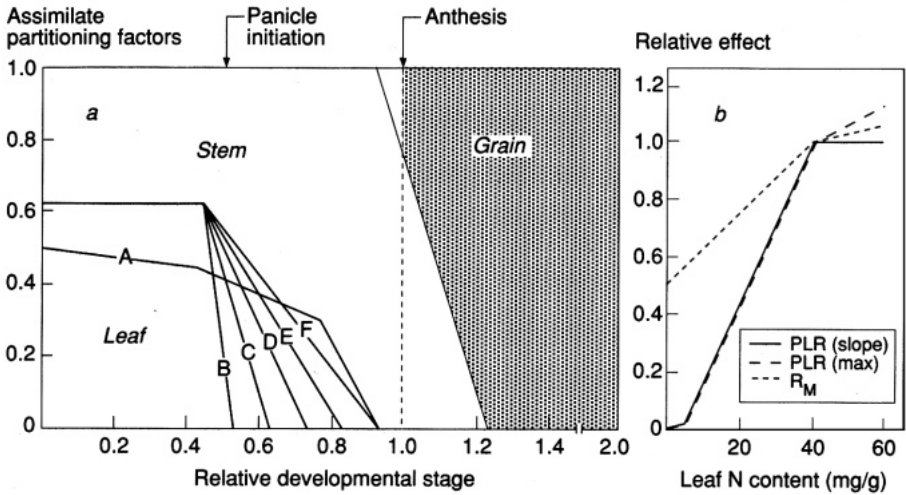
When L3QT was evaluated for rice crops under optimal growth conditions (Herrera-Reyes and Penning de Vries 1990), it was found to simulate rice growth rates quite well, provided that accurate initial values are supplied. The model also includes physiological responses to crop N status and permits detailed photosynthesis calculations.

Differences in L3QT from previously documented models are described below. Water stress is supposed not to occur in an irrigated crop and was therefore not simulated in this study. The crop parameters used are those for rice variety IR64.

In L3QT, the foliage is explicitly subdivided into three horizontal strata of equal area but different N concentrations. Leaf N concentration affects the rate of several processes (Fig. 1b).

- Leaf photosynthesis. The leaf gross photosynthesis radiation response curve is quantified by two parameters: the initial slope (quantum efficiency) at low light levels and the maximum photosynthesis rate at high light levels. The maximum rate is almost proportional to N concentration (Penning de Vries et al 1990, Dingkuhn et al 1990e). Quantum efficiency is supposedly related to this concentration at low N levels. This assumption, supported by observations (Dingkuhn, unpubl. data), was necessary to simulate low rates of CER measured in field crops with low N. Crop production is relatively sensitive to these parameters.
- Maintenance respiration. The rate is related to leaf N concentration, but only half as much maximum leaf photosynthesis depends on N (Penning de Vries et al 1990). Maintenance respiration of the other organs is related to N concentration in the same way. Relationships between dark respiration and canopy N content were established by Ingram et al (1990).
- Senescence and loss of leaves. Following Van Keulen and Seligman's (1987) findings in wheat crops, we related the rate of death of leaves in a given stratum to their N concentration. The amounts of green and dead leaves are calculated separately for each stratum, with leaf death proceeding successively from the lower to the upper layer.

Total N content of the leaves is an input in L3QT because there is not yet a model that can reliably simulate that variable. Another reason is that this study focused on crop



1. a) Patterns of assimilate partitioning among the foliage, stems, and grains used in growth simulation. Pattern A is the actual partitioning in IR64 rice. Patterns B to F are hypothetical. Root assimilate allocation is controlled separately. b) Relationships between leaf N concentration and gross photosynthesis (PLR) (maximum rate and the initial slope of light response) and maintenance respiration ( $R_M$ ). At 40 mg N/g, the initial slope is 0.4 kg CO<sub>2</sub>/ha per h (J/m<sup>2</sup> per s), the maximum rate is 66 kg CO<sub>2</sub>/ha per h, and  $R_M$  is 0.02 kg glucose/kg.

responses to certain N content in the canopy, not on ways to realize N uptake. In our experiments, N content of the green leaves was determined by sequential sampling throughout the season. L3QT determines average leaf N concentration by dividing N content by leaf weight. We preferred to use N content rather than N concentration as the input because quantity is a more stable feature than concentration.

Vertical distribution of N in the foliage was empirically measured for only one developmental stage, season, and variety (Dingkuhn et al 1990e). But our model shows it to be essential in understanding growth dynamics. In L3QT, the foliar N concentration of the central stratum equals the average, that of the lower layer is lower by a certain value, and that of the upper layer higher by the same value. This value was 10 mg N/g (1%) or less if it would decrease N concentration in the lower layer below the minimum 0.4%, in line with findings in experiment 6 (Dingkuhn et al 1990e). Total amount of N in the leaves is not affected by the gradient.

We found that L1Q's feedback of glucose levels on photosynthesis was too strong under conditions that allowed rapid growth, and eliminated it. The state variable weight of "storage organ" was redefined as "weight of grains," since the assimilating function includes formation of the empty panicle (under stem formation). Where not explicitly stated, grain yields were expressed at zero moisture.

Most crop parameters for IR64 were taken from Penning de Vries et al (1989) and Herrera-Reyes and Penning de Vries (1990). The pattern of assimilate partitioning

between leaves and stems followed pattern A in Figure 1, which best approximated the data for IR64 across crop establishment methods and N rates. It has been reported to be independent of crop N level (van Heemst 1986); this was confirmed in our experiments. The pattern of partitioning between roots and shoots was derived from observations by Diekmann (IRRI, pers. comm.). The fraction of stem reserves mobilized for grain growth was raised to 40% to simulate the significant weight loss of stems after flowering. The rates of phenological development were adjusted slightly to match the dates of flowering and maturity in our experiments.

Differences among crop establishment methods have no consequence for the structure of L3QT, and are only expressed in the initial values for crop weight and the pattern of crop N content.

To verify L3QT and evaluate the growth and yield formation processes, data from experiment 4 were used. Simulation started at 27 d after seeding (DAS) for direct seeded treatments and 21 d after transplanting (DT) for transplanted treatments. Initial dry weights of the various plant parts were used as inputs.

Meteorological data recorded at the experimental sites were used as inputs for model verification. For the extrapolations, 10-yr historic data for the IRRI farm were used (1979-88). This permitted us to determine both the average and standard deviation of growth dynamics and yield for our hypothetical crops in the dry and wet seasons.

## Results and discussion

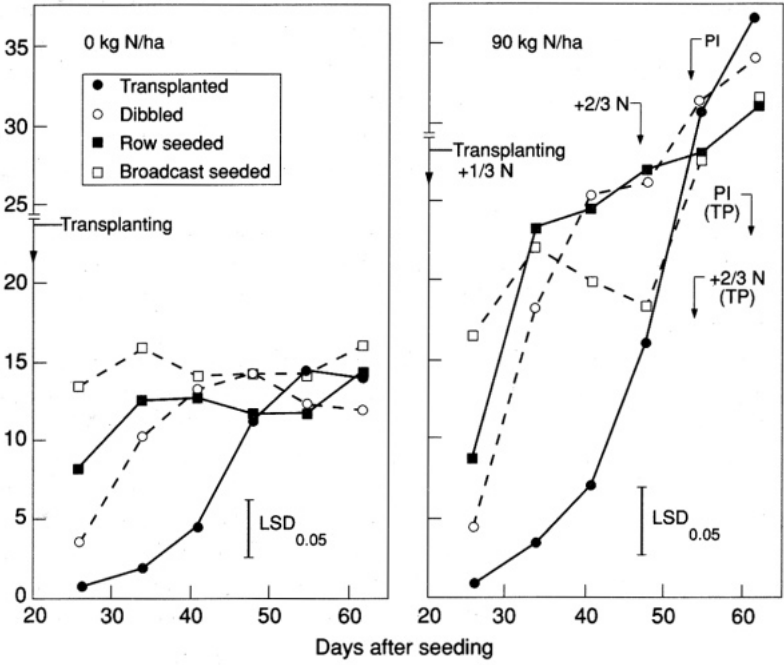
### Field observations

*Growth and yield analyses of broadcast-seeded, row-seeded, dibble-seeded, and transplanted rice.* Crop growth is a function of a population's cumulative assimilation of CO<sub>2</sub>. For medium-duration (110-124 d) cultivar IR64, CER was measured during all growth stages in all treatments (Fig. 2). Differences among planting methods were small at panicle initiation (PI) but highly significant during the first 45 d of growth.

Broadcast-seeded rice had the highest initial CER, due to its great population density, followed by row-seeded rice. Dibbled rice, which had the same population density and geometry as transplanted rice, had significantly higher CER than transplanted rice. This difference was attributed to the growth inhibition caused by transplanting shock (Dingkuhn et al 1990c). Application of N fertilizer increased CER for all planting methods but did not eliminate the basic differences caused by transplanting shock. Consequently, direct seeded rice had a substantial growth advantage over transplanted rice during vegetative growth, resulting in greater biomass (data not presented) and leaf area (Fig. 3).

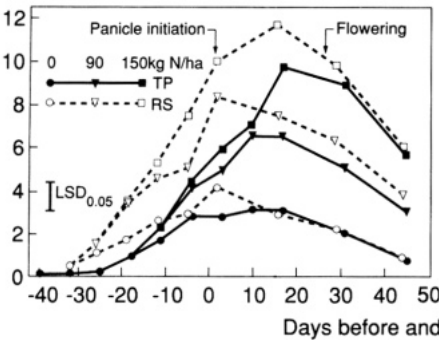
The initial growth advantage of dibble-seeded, row-seeded, and broadcast-seeded rice over transplanted rice carried over into the subsequent growth stages, generating a higher LAI under any fertilizer regime. The proliferation of foliage, however, was associated with a rapid decrease in foliar N content, due to the dilution of absorbed N in the plant tissues shown at the right in Figure 3.

CER ( $\mu\text{mol CO}_2/\text{m}^2$  per s)

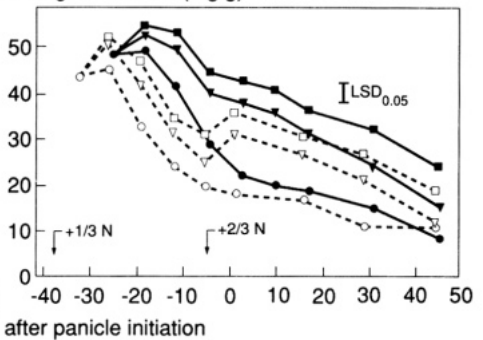


2. Effect of planting method and N fertilizer application on canopy  $\text{CO}_2$  assimilation rates (CER) during the vegetative growth phase of IR64 rice. Experiment 3, Muñoz, Nueva Ecija, Philippines, 1987 dry season. PI = panicle initiation.

Leaf area index



Foliage N content (mg/g)



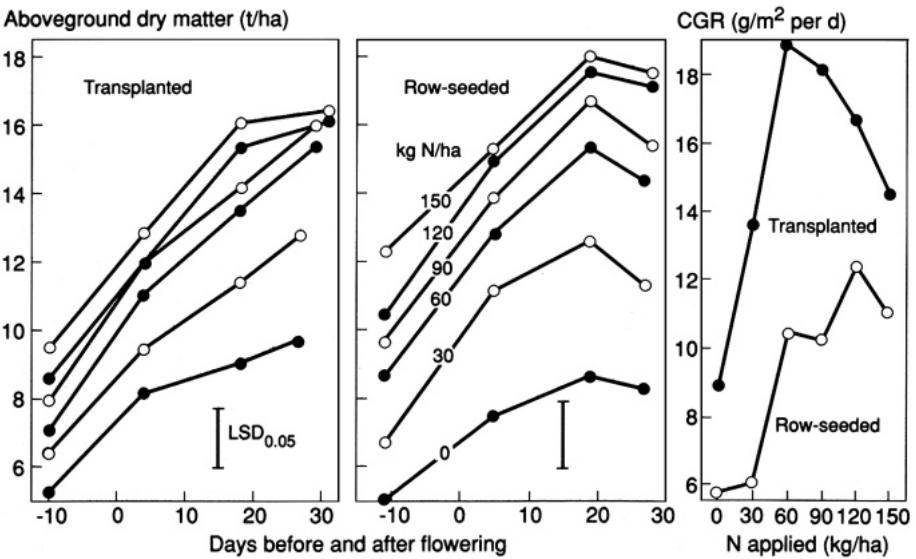
3. Effect of N fertilizer application on leaf area index and foliage N concentration of transplanted (TP) and row seeded (RS) IR64 rice, Experiment 4, Muñoz, Nueva Ecija, Philippines, 1988 dry season.

Low foliar N concentration during reproductive growth of dibble-seeded, row-seeded, and broadcast-seeded rice depressed CER (Schnier et al 1990a, Dingkuhn et al 1990a) and resulted in low crop growth rates (CGR) during ripening (Fig. 4). The CGR at flowering and thereafter is an important determinant of grain yield and harvest index (HI) (Akita 1989; Dingkuhn et al 1990b,d,e).

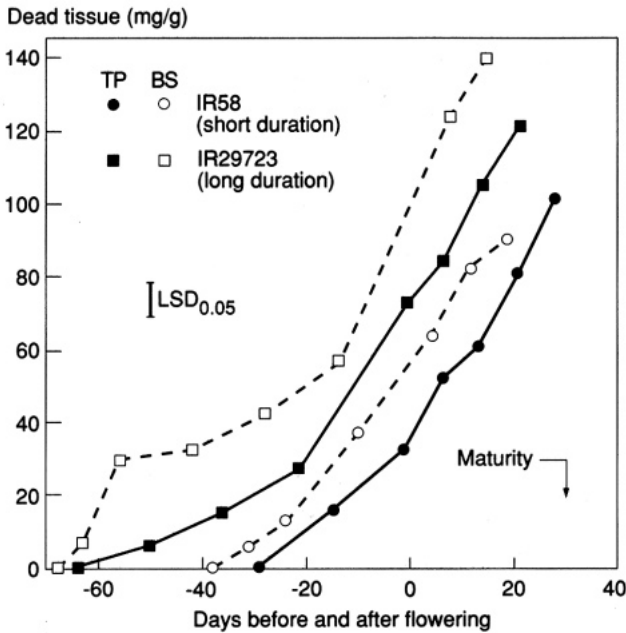
CGR during ripening responded to N fertilizer rate in an optimum-shaped function. To reach maximal CGR, higher N rates were required by row-seeded than by transplanted rice.

The low CGR during ripening of row-seeded rice was probably due to high biomass, and thus, to maintenance respiration (Dingkuhn et al 1990a), in combination with low foliar N concentration (Fig. 3), and reduced CO<sub>2</sub> assimilation rates (Yoshida 1981, Dingkuhn et al 1990e).

Another characteristic of direct seeded rice was phenologically early onset of senescence and, thus, tissue death (Fig. 5). Tissue death during the reproductive growth phase of monocarpic crops is usually associated with the transfer of carbohydrates, N, and P from the vegetative tissues to the reproductive organs (Biswas and Choudhuri 1980, Yoshida 1981). A substantial increase in necrotic tissue, however, occurred from 25 to 65 d before flowering, depending on cultivar and planting method. Senescence was observed phenologically earlier in a broadcast-seeded crop than in a transplanted crop, and earlier in a long-duration (IR58) than in a short-duration cultivar (IR29723). Preflowering senescence of medium-duration IR64 was intermediate (data not presented).



4. Effect of N fertilizer rate in transplanted and row-seeded IR64 rice on dry matter accumulation during ripening phase and crop growth rates (CGR) between flowering and maturity. Experiment 4, Muñoz, Nueva Ecija, Philippines, 1988 dry season.

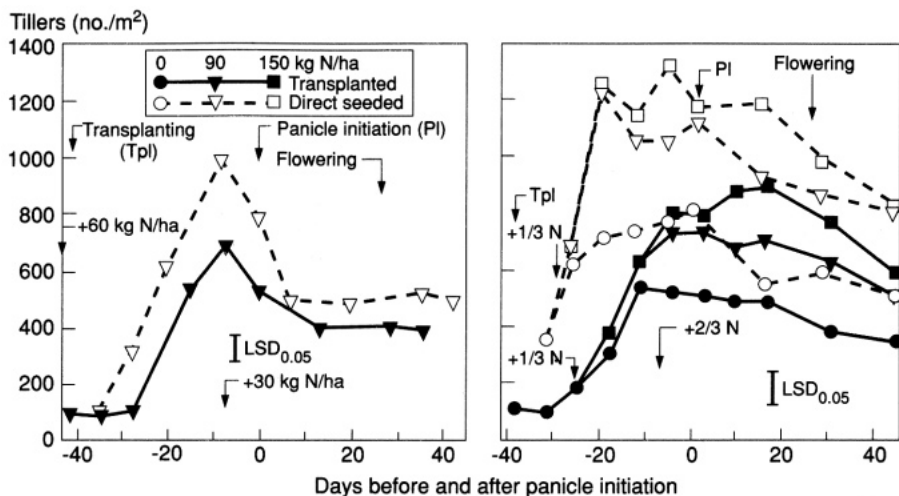


5. Relative accumulation of dead shoot tissue during the reproductive growth phases of transplanted (TP) and broadcast seeded (BS) IR58 and IR29723 rice fertilized with 90 kg N/ha. Experiment 5, Muñoz, Nueva Ecija, Philippines, 1988 dry season.

Senescence was delayed by high N rates (Dingkuhn et al 1990a) and late season foliar N application (Dingkuhn et al 1990d,e; data not presented), indicating that preripening senescence is influenced by the N status of photosynthesizing tissues. Considering that direct seeded rice absorbed as much or higher amounts of N as did transplanted rice (Schnier et al 1990a,b), and that it had consistently lower foliar N concentration, we conclude that, when directly seeded, IR64 and similar rice cultivars have a tendency to develop foliar N deficiency. This N deficiency, in turn, results in low CER and CGR, and in early onset of senescence.

The patterns of tiller production and abortion across time (Fig. 6) were associated with planting method and N fertilizer regime in a manner similar to those of LAI shown in Figure 3. Phenologically, tillering began earlier in dibbled than in transplanted rice; this resulted in higher tiller number/area throughout the season. Tiller production was excessive, and thus was followed by a distinct abortion phase, particularly in direct seeded treatments.

Schnier et al (1990b) and Dingkuhn et al (1990b) showed that tiller production and abortion are linearly related to relative growth rate (RGR) throughout vegetative and early reproductive growth. Relative growth rates are generally high during initial growth, enabling high tillering rates during the establishment phase of direct seeded rice. On the other hand, this early period of high tillering potential in transplanted rice



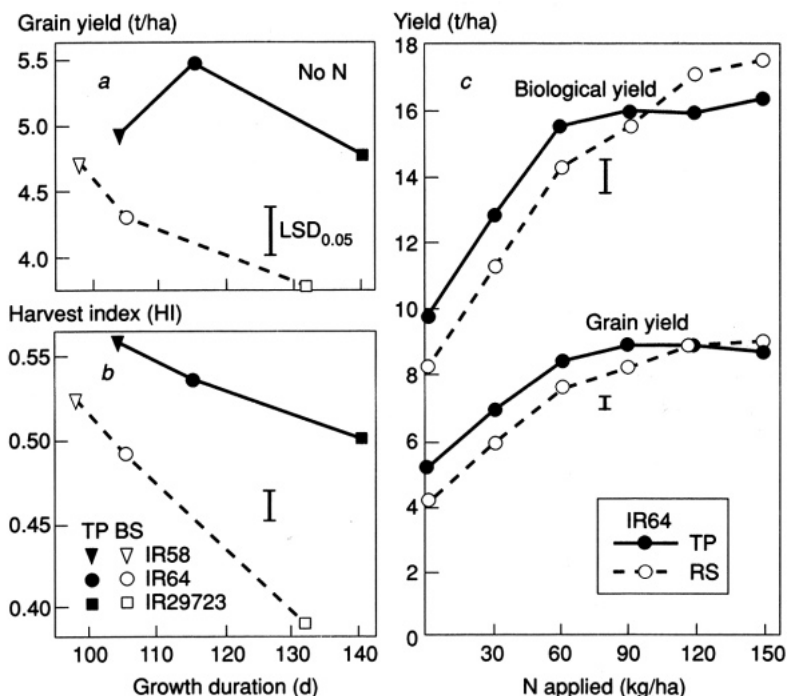
6. Tiller number of transplanted and direct seeded IR64 rice. Left: Transplanted and hill-wise dibbled rice having the same initial population (100 plants/m<sup>2</sup>) and planting geometry, Experiment 1, IRRI, 1986 dry season. Right: Transplanted (100 plants/m<sup>2</sup>) and row seeded rice (180 plants/m<sup>2</sup>) fertilized with 0, 90, and 150 kg N/ha. Experiment 4, Muñoz, Nueva Ecija, Philippines, 1988 dry season.

falls into a growth lag caused by transplanting shock. Consequently, transplanting shock not only delays, but also reduces tiller production.

As a result of the differences in tillering behavior, direct seeded rice in general had more panicles/area but fewer spikelets/panicle and, eventually, fewer grains/panicle (Schnier et al 1990a; Dingkuhn et al 1990d,e; data not presented). When N inputs were low, grain yields were lower in broadcast-seeded and row-seeded rice (Fig. 7) than in transplanted rice. However, with 120-150 kg N/ha, the differences in grain yield among planting methods disappeared. Direct seeded rice seems to require greater N resources than does transplanted rice, to escape the N deficiency during the late season that reduces yield. Potential yields, however, were not affected by crop establishment method.

Direct seeded rice consistently had a lower HI than transplanted rice (Dingkuhn et al 1990c, Schnier et al 1990a). The HI is positively associated with foliar N concentration and CGR at flowering (Dingkuhn et al 1990d,e; Akita 1989). As a general trend, differences in foliar N content, grain yield, and HI among planting methods were smallest for short-duration rice. The performance of direct seeded rice became increasingly inferior to that of transplanted rice as growth duration increased (Dingkuhn et al 1990b).

In summary, short-duration cultivar IR58 gave its highest yields when broadcast seeded and fertilized with 90 kg N/ha (Dingkuhn et al 1990b). For this cultivar, the vegetative growth phase in transplanted treatments (with productivity reduced by



7. *a* and *b*: Effect of growth duration on grain yield and harvest index of transplanted (TP) and broadcast-seeded (BS) rice. Experiment 5, Muñoz, Nueva Ecija, Philippines, 1988 dry season. *c*: Effect of fertilizer N rate on grain and biological yield of TP and row-seeded (RS) rice. Experiment 4, Muñoz, Nueva Ecija, Philippines, 1988 dry season.

transplanting shock) was too short to build up sufficient yield potential. However, dense populations resulted in superior vegetative growth and tillering, and, consequently, higher grain yields.

For medium-duration cultivar IR64, higher yields under direct seeding were achieved when the crop was dibbled and 2/3 of the N fertilizer band-placed at midseason (Schnier et al 1988, 1990b). This treatment combination resulted in relatively low tillering and high foliar N content, achieving high HI and grain yield. For long-duration cultivar IR29723, no treatment combination raised direct seeded grain yield above transplanted yield.

The current tropical semidwarf rice plant type gives maximal grain yields under transplanted culture if the vegetative growth phase is long enough to provide the necessary yield potential. Under direct seeded culture, high grain yields require greater N resources than they would with transplanting, and shorter growth duration to prevent vegetative overgrowth.

*Growth- and yield-limiting properties of the canopy at flowering.* The results presented in Figures 2-7 indicate that tiller and leaf area production are excessive in

direct seeded medium- and long-duration cultivars, while foliar N concentration is suboptimal during reproductive and ripening phases.

A canopy stratification study of broadcast-seeded and transplanted IR72 rice (experiment 6) at anthesis provided insights into limitations to yield. Grain yield was linearly correlated with CER at anthesis ( $r = 0.91^{**}$ ). Similarly, CER/productive tiller determined grain yield/panicle, with broadcast-seeded rice having a much lower CER/tiller and, thus, lower grain yield/panicle than transplanted rice.

Harvest index depended on N concentration in the flag leaf ( $r = 0.75^{**}$ ). The lower HI of broadcast-seeded rice, therefore, was probably partly caused by a lower flag leaf N concentration. Nitrogen limited leaf  $\text{CO}_2$  assimilation rates (CAR) for all leaf positions, including the flag leaf (which had the greatest N concentration). The contribution of lower leaf positions to yield was insignificant.

CER at anthesis was positively correlated with plant N uptake, N concentration, and CAR of the flag leaves, and negatively correlated with tiller number (Dingkuhn et al 1990e). A multiple, stepwise regression analysis of HI against various properties of the canopy at anthesis identified CER and N concentration of the flag leaf to be positively correlated with HI and LAI, and N concentration of the lower leaf positions to be negatively correlated with HI.

We conclude that to maximize HI and grain yields for broadcast-seeded rice, a moderate tiller number and LAI in combination with high foliar N concentration are required. Much of the foliar N should be located in a photosynthetically active form in the flag leaf, while N contained in the lowest leaf positions should be made available for growth of grain. In other words, spikelets should receive their N from the lower plant parts and their C from the uppermost leaves.

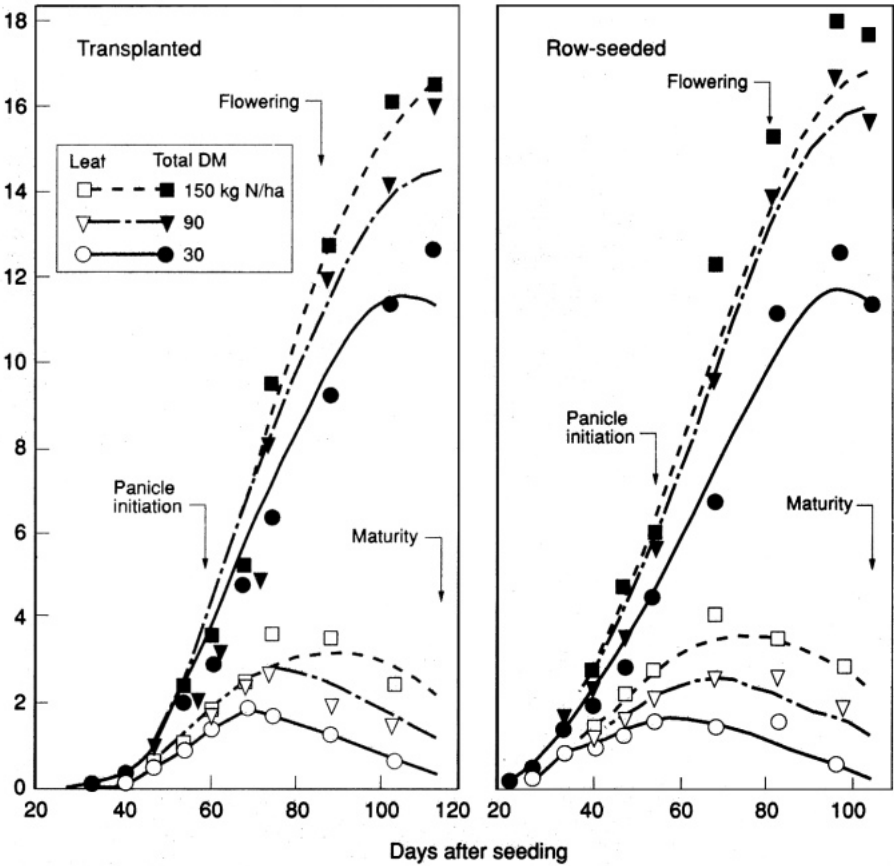
An additional source of carbohydrates for spikelet filling is the reserves located in the stem and leaf sheaths (Chaturvedi and Ingram 1990). If direct seeded rice plants are to allocate less dry matter to foliage while having high CER, an expanded reserve organ for assimilates produced prior to spikelet filling is needed.

The potential to further improve dry matter production and grain yield of irrigated rice does exist, particularly when the crop is direct seeded. The necessary changes in the architecture of the crop's canopy, however, are difficult to achieve through alternative cultural practices alone (Schnier et al 1990b; Dingkuhn et al 1990d,e).

## Simulation of rice genome modifications

The performance of the L3QT model in computing crop growth and yield was evaluated by simulating all trials of experiment 4. Figure 8 shows measured and simulated growth curves for three levels of N. Intermediate growth parameters evaluated were average leaf N concentration, CER, leaf area dynamics, tillering, and HI (data not presented). The agreement of trends in all cases and of absolute values in most cases gave us the confidence to conclude that L3QT can be used to explore the benefits of different new plant type designs for yield and nitrogen use efficiency. We

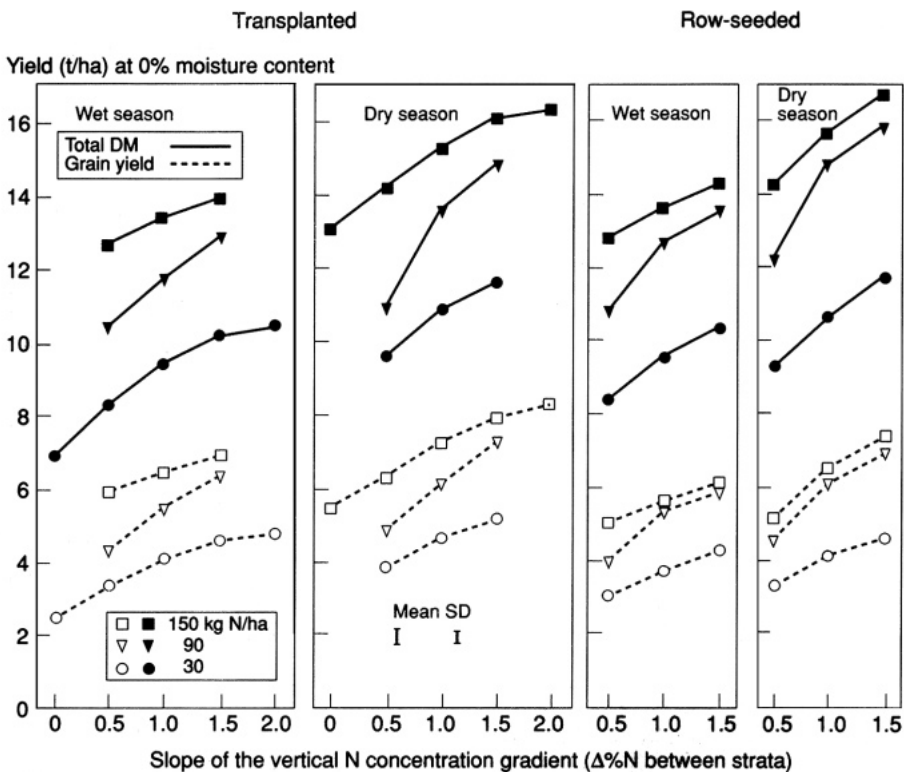
Dry matter (t/ha)



8. Simulated (solid and dashed lines) and measured (points) dry matter accumulation aboveground and in the leaves of transplanted and row seeded IR64 rice fertilized with 30, 90, or 150 kg/ha. Experiment 4, Muñoz, Nueva Ecija, Philippines, 1988 dry season.

investigated several features; the most promising are presented here. Most of these features affect production, irrespective of crop establishment method.

*The N gradient.* The impact of modifying the vertical N concentration gradient in the foliage across three strata was investigated. Growth kinetics and dry matter yield were simulated for six N rates and two crop establishment methods (transplanting and row seeding), for constant gradients from 0 to 4% (differences between the upper and central and the central and lower strata of 0-2% N, with the upper layer having the highest concentration). Figure 9 shows the mean effects and standard deviation of these gradients on the biological and grain yields for transplanted and row-seeded IR64 rice crops, fertilized at three levels, in the wet and dry seasons. Nitrogen distribution



9. Simulated mean dry matter (DM) and grain yields for wet and dry seasons across 1979-88 for transplanted and row-seeded IR64 rice, fertilized with 30, 90, or 150 kg N/ha. The difference in foliar N concentration between the top and bottom strata was treated as a variable. Vertical bars indicate standard deviation. IRRI, 1979-88.

appears to have a significant effect on both biological and grain yields; the effects are roughly similar in both crop establishment methods and across N regimes and seasons. This is in particular brought about by the higher productivity per amount of leaf N during the reproductive period.

A similar effect can be achieved by increasing the total amount of N in the crop, but this crude solution would require more fertilizer and would be less efficient. It is therefore suggested that increasing the vertical N gradient in the foliage offers an opportunity to increase yields at a constant level of N input. A canopy stratification study using IR72 rice (Dingkuhn et al 1990d,e) gave empirical support to these predictions: grain yields were correlated positively with flag leaf N content; N in the lower leaf strata had little or no impact.

The numerical value of the gradient might depend on the level of N applied to the crop. To test this, we determined the best fit of simulations to the experimental data.

When the N rate was low to moderate (30-90 kg N/ha) in row-seeded rice and low to high (30-150kgN/ha) in transplanted rice, the best fit was for a difference of 1.0-1.25% N (Table 1). For zero N (controls), smaller gradients (0.5-0.75% N) gave the best fit. With high inputs (120-150 kg N/ha), steeper gradients (1.5-1.75% N) fitted the row-seeded treatments best.

This suggests that the vertical foliar N gradient depends on the N rate. Downward adjustment of the N concentration in the leaves that become shaded could be the mechanism that leads to a gradient. Optimizing the efficiency of absorbed N for crop production would result from the process.

Further studies are needed to determine the vertical foliar N concentration gradient in rice crops, and to establish its responsiveness to N inputs, development stage, LAI, and radiation levels. The distribution of N within leaf blade, and thus, the leaf angle, will affect the gradient as well. There may be significant differences among rice varieties.

We have not found reports on the significance of this aspect of photosynthesis and N distribution, but the topic invites further analysis by modeling and field research. No difference between strata makes the N concentration of layers equal. This case corresponds to a model in which the N concentration of all leaves equals the measured average value (e.g., Van Keulen and Seligman 1987). However, this can lead to a significant underestimation of crop yield. In our examples, underestimation amounted to about 1 t/ha (Fig. 9).

*Modifications in the leaf-stem ratio.* Because maximum leaf area in the row-seeded crop appeared to be excessive, we simulated the consequences of producing fewer leaves. The pattern of assimilate partitioning between leaves and stems is an important determinant of potential production (Potter and Jones 1977). In its basic version, L3QT uses a partitioning pattern where during early vegetative growth, new assimilates not partitioned to the root and not consumed by respiration processes are divided equally between foliage and stem (pattern A in Figure 1). The fraction consumed for leaf growth subsequently decreases to zero at booting. This is followed by activation of the reproductive sink, which then attracts all new assimilates and mobilizable reserves until either the sink is saturated or the source exhausted.

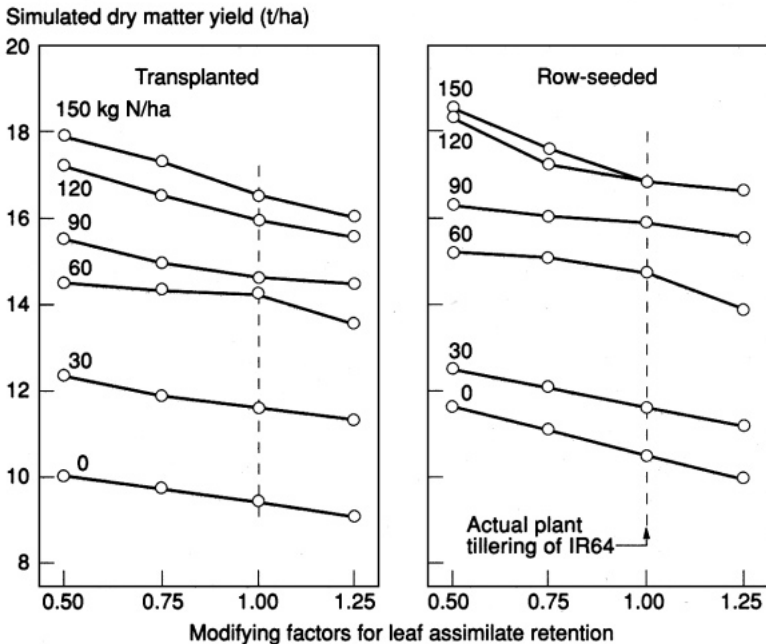
**Table 1. Simulated vertical N concentration gradients between top and bottom strata in the foliage, giving the best fit to growth and yield of transplanted and row-seeded IR64 rice (experiment 4).**

N applied (kg/ha)	Gradient (delta % N)	
	Transplanted	Row-seeded
0	1.5	1.0
30	2.0	2.0
60	2.5	2.5
90	2.5	2.5
120	2.5	3.0
150	2.5	3.5

Two types of modifications of assimilate partitioning were evaluated: modifying the leafiness of the crop by an overall reduction or increase of the assimilate fraction for leaves, and modifying leaf area dynamics by an increase in the fraction for leaves in young plants and a reduction later.

Simulation of an overall lower or higher fraction of assimilates for leaf growth (pattern A in Figure 1 multiplied by 0.5, 0.75, or 1.25) showed consistent but small effects on dry matter production (Fig. 10). The least leafy canopy gave the highest dry matter yields at all N rates and for all crop establishment methods. Reduced leaf production, with the resulting higher N concentration in the foliage, can be expected to moderately improve biological yields (transplanted rice, 6.0%; row-seeded rice, 7.3%). The benefit comes from greater CO<sub>2</sub> assimilation and reduced maintenance respiration during reproductive growth, which exceeds the loss brought about by a delayed establishment of full crop cover.

To approximate a leaf production pattern that would lead to maximum crop growth rates, partitioning patterns B to F in Figure 1a were tested for transplanted and row-seeded rice at low, medium, and high N levels. Partitioning patterns that enhanced leaf growth during early stages (until 45 DAS), with a subsequent sharp decline in



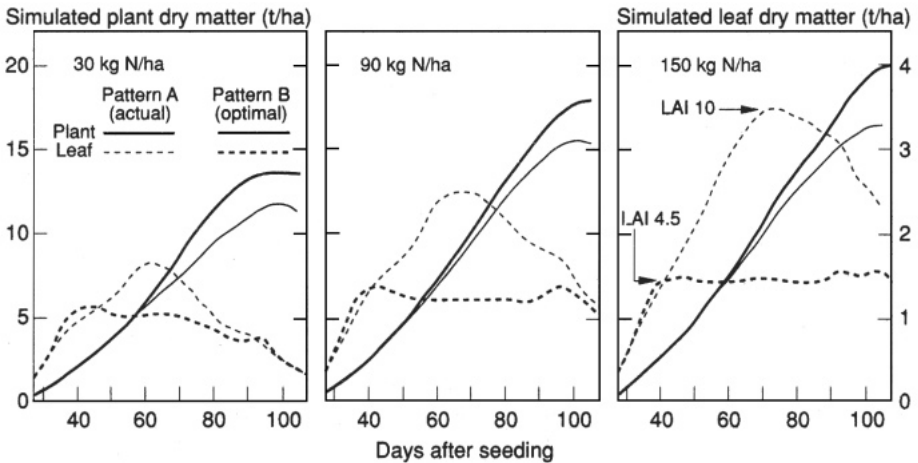
10. Simulated dry matter yields of transplanted and row-seeded flooded IR64 rice at various N rates, treating foliar assimilate retention for leaf growth as variable. Factor 1.0 left the pattern of foliar assimilate retention (pattern A in Fig. 1) unchanged. Factor 0.5 reduces relative leaf growth by 50% and enhances assimilate export accordingly.

**Table 2. Simulated effects of assimilate partitioning patterns (A-F) on biological (BY) and grain (GY) yield of transplanted (TP) and row-seeded (RS) flooded rice (experiment 4).<sup>a</sup>**

	Yield (t/ha)											
	A		B		C		D		E		F	
	GY	BY	GY	BY	GY	BY	GY	BY	GY	BY	GY	BY
TP 30 N	5.2	11.4	5.4	11.2	<u>6.0</u>	<u>13.2</u>	5.8	12.7	5.7	12.6	5.3	12.8
TP 90 N	7.8	14.4	7.1	13.7	<u>8.5</u>	<u>16.9</u>	7.8	15.9	7.4	15.1	7.0	14.7
TP 150 N	8.1	16.5	7.8	14.9	<u>9.7</u>	<u>18.6</u>	9.5	18.5	8.7	17.4	8.1	16.6
RS 30 N	4.4	11.3	5.2	12.3	<u>5.3</u>	<u>13.1</u>	5.1	12.7	4.7	12.0	4.5	11.5
RS 90 N	6.9	15.8	<u>7.6</u>	<u>17.7</u>	7.2	17.5	7.0	16.7	6.9	16.0	6.9	15.8
RS 150 N	6.7	17.1	<u>8.1</u>	<u>19.9</u>	7.6	19.3	7.3	18.5	7.2	17.6	6.9	17.1

<sup>a</sup> Pattern A represents the best fit to empirical IR64 data. Patterns B to F are hypothetical patterns, as shown in Figure 1a. Underlined results indicate the apparent optimal partitioning pattern for the treatment.

production of new leaves, increased grain yield by 10-25% (0.8-1.6 t/ha) (Table 2). Growth curves for the actual (A) and the optimized pattern (B for row-seeded, C for transplanted rice) of assimilate partitioning were significantly different (Fig. 11). The optimized patterns exhibited faster canopy establishment, followed by maintenance of a low to moderate leaf mass (1.0-1.6 t/ha, equivalent to a LAI of 2.9-4.6, depending on N rate) for much of the season. Foliar N concentration remained higher than that in the actual pattern throughout the reproductive phase and well into the ripening phase (data not presented); photosynthesis and dry matter production were particularly high during mid- and late season.



11. Simulated dry matter accumulation aboveground and in the leaves of row-seeded IR64 rice at three N rates. Simulation used assimilate partitioning pattern A (actual partitioning) and an optimized pattern (B for row-seeded rice, C for transplanted rice as shown in Figure 1a).

Such an improved partitioning pattern requires increased retention of assimilates in the foliage before PI, but a halt in leaf production once a moderate LAI is reached. The period with an increased rate of leaf production coincides with the main phase of tiller production. Reduced tillering, a desirable trait in cultivars adapted to direct seeding (Dingkuhn et al 1990a, Schnier et al 1990b), would free assimilates for leaf formation. Research is needed to determine whether the improved partitioning pattern is biologically possible.

*Extended vegetative and ripening phases.* The durations of the vegetative and ripening phases of rice depend on genotype, temperature, and daylength (vegetative phase only). Most modern, high-yielding rices grown under tropical conditions are photoperiod-insensitive, have a growth duration of 100-130 d, and ripen 25-30 d after anthesis. Because temperatures are higher in the tropics, this ripening phase is short compared with that of rice and other cereals grown in the temperate zone (Penning de Vries et al 1989, Angus et al 1981). Because there is a maximum rate of grain growth, the short duration of ripening puts a relatively low ceiling on the potential yield of tropical rice. Lengthening that phase raises the ceiling. Temporary storage of assimilates in the stem can carry over some photosynthesis from before flowering to grain formation, so that a longer vegetative phase can be beneficial as well.

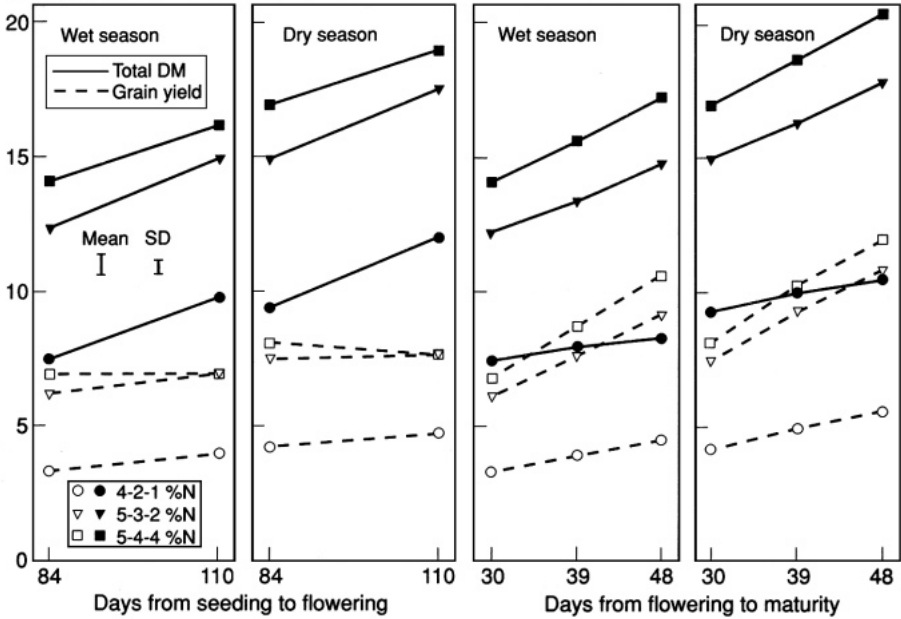
We simulated the effect of extending the vegetative and ripening phases by 30 and 60%. Growth patterns were compared in crops with rapidly declining average foliage N concentrations (4% N initially, 2% at flowering, and 1% at maturity), slowly declining concentrations (5, 3, and 2%, respectively), and consistently high concentrations (5, 4, and 4%, respectively). The first case resembles a crop fertilized with N at a moderate level; the second, a crop fertilized at a high rate. The last case shows the yield that would be attained if the foliage did not have to provide N to the grain.

Extending the duration from seeding to flowering by 30% (from 84 to 110 d) strongly enhanced biological yield but did not significantly affect grain yield (Fig. 12), and HI was consequently lower. Such results agree with field observations (Dingkuhn et al 1990b). The expected benefit from extra reserves was lost to increased maintenance respiration.

Extending the ripening phase from 30 to 39 or 48 d improved both biological and grain yields, provided that foliar N concentration remained high. Prolonging the ripening phase by 9 d improved simulated grain yield by up to 25%; prolonging it by 18 d improved yield by 50%, leading to top grain yields of 9.5-11.5 t/ha with 39 d ripening and 11.5-13.5 t/ha with 48 d ripening (expressed at 14% moisture). The HI increased to about 0.62. We suggest that more attention be given to prolonging the reproductive phase of tropical rice and to keeping foliar N concentration high.

A longer reproductive phase requires lengthening the period of spikelet filling. For our simulation runs, the sink capacity of the panicle was set to be nonlimiting. The maximum size of individual rice grains appears to be genetically fixed, with the maximum usually approached near maturity. An improved crop should therefore have an increased number of active spikelets filled in a staggered manner or at a slower rate. To a lesser degree, staggered filling is already realized in existing rice cultivars; they

Yield (t/ha) at 0% moisture content



12. Simulated mean effects of a hypothetical prolongation of the vegetative growth phase by 30% and the ripening phase by 30 or 60 on dry matter and grain yields in IR64 rice over 10 yr, (1979-88). Foliar N concentration was assumed to decrease from crop establishment through heading to maturity following the patterns 4-2-1, 5-3-2, or 5-4-4% N (wt/wt).

exhibit early maturation in distant spikelets and late maturation in proximal spikelets and spikelets of higher order (Dingkuhn, unpubl. results).

*Combined improvements.* If the suggested crop improvements were combined in a single simulation run, still higher yields would be predicted. However, we refrained from doing so because further discussion of the individual aspects is needed first, and because some improvements may be physiologically conflicting.

Most of the simulated yield increases are brought about by combining a longer duration of the green leaf area and sustained photosynthesis rate. Since the N concentration of the grain should not be affected, the increase in yield implies that grains require a proportional amount of extra N. However, most N in the grain is currently provided through translocation from the leaves, where it is needed for photosynthesis. To avoid self-destruction (Sinclair and de Wit 1975) and to realize a major increase in grain yield, it is imperative that alternative sources of N be utilized, such as reserves in stems (Penning de Vries et al 1990) or sustained uptake. Research on N redistribution mechanisms and their variability among rice cultivars is needed.

Another aspect of rice with an improved assimilate source during reproductive growth that needs attention is sink capacity. Although an improved N status between

PI and heading (which is one of the characteristics of the proposed plant types) usually also increases the number of spikelets initiated and differentiated (Dingkuhn et al 1990d), the potential sink size of current cultivars may not match the assimilate supply offered in new plant types. Larger panicles with more spikelets and a lower percentage of degenerated spikelets are required.

## Conclusions

Field experiments showed that modern, high-yielding semidwarf rices can yield up to 9 t/ha (at 14% moisture) under both transplanted and direct seeded flooded culture. A direct seeded crop, however, requires greater N input than a transplanted crop to achieve its maximum yield. This difference is associated with overproduction of vegetative material (leaves, tillers) in direct seeded rice during the period of linear growth, resulting in dilution of resorted N and, subsequently, foliar N deficiency. Consequently, direct seeded rice had lower growth rates during the ripening phase, and earlier senescence and lower HI than transplanted rice. The higher planting density of a row- or broadcast-seeded crop and the absence of transplanting shock accounted for these characteristics. Although alternative cultural practices can improve yield and fertilizer N efficiency, new plant types might be more effective.

Simulations indicate that changes in the canopy would enable both direct seeded and transplanted flooded rice to achieve higher yields. The beneficial effects, however, would be greater in direct seeded rice because, under transplanted culture, growth characteristics already show a certain resemblance with the projected optimum (lower tillering, less leaf area, higher foliar N concentration). Assuming that the absolute amount of N allocated to the foliage remains unchanged, the following modifications of N and assimilate partitioning would improve yields:

- prolong the ripening phase,
- maintain a high N concentration in the leaves,
- increase the slope of the vertical N gradient in the foliage,
- allocate more assimilates to leaf growth in young crops,
- reduce leaf growth during the late vegetative and reproductive phases, and
- expand the assimilate storage capacity of the stems.

With respect to broadcast-seeded rice, these improvements should be combined with the following plant characteristics:

- improved seedling anchorage,
- reduced tillering ability,
- longer life span and larger size of flag leaves, and
- larger panicles and higher sink capacity.

Simulation results indicate that the current yield barrier observed in modern tropical rices can theoretically be raised substantially, provided that it is possible to generate new plant types with modified N and assimilate partitioning patterns and/or a more productive and longer ripening phase. Grain yield increases from a combination of these changes would probably exceed 25%. The biological feasibility of the concepts

outlined, however, requires verification through physiological studies and analyses of the existing rice gene pool.

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## Notes

*Acknowledgment:* The authors wish to express their gratitude to the German Agency for Technical Cooperation (GTZ), Germany, and the Directorate for International Development Cooperation (DGIS), The Netherlands, for their financial support.

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Rationale for a low-tillering rice plant type with high-density grains

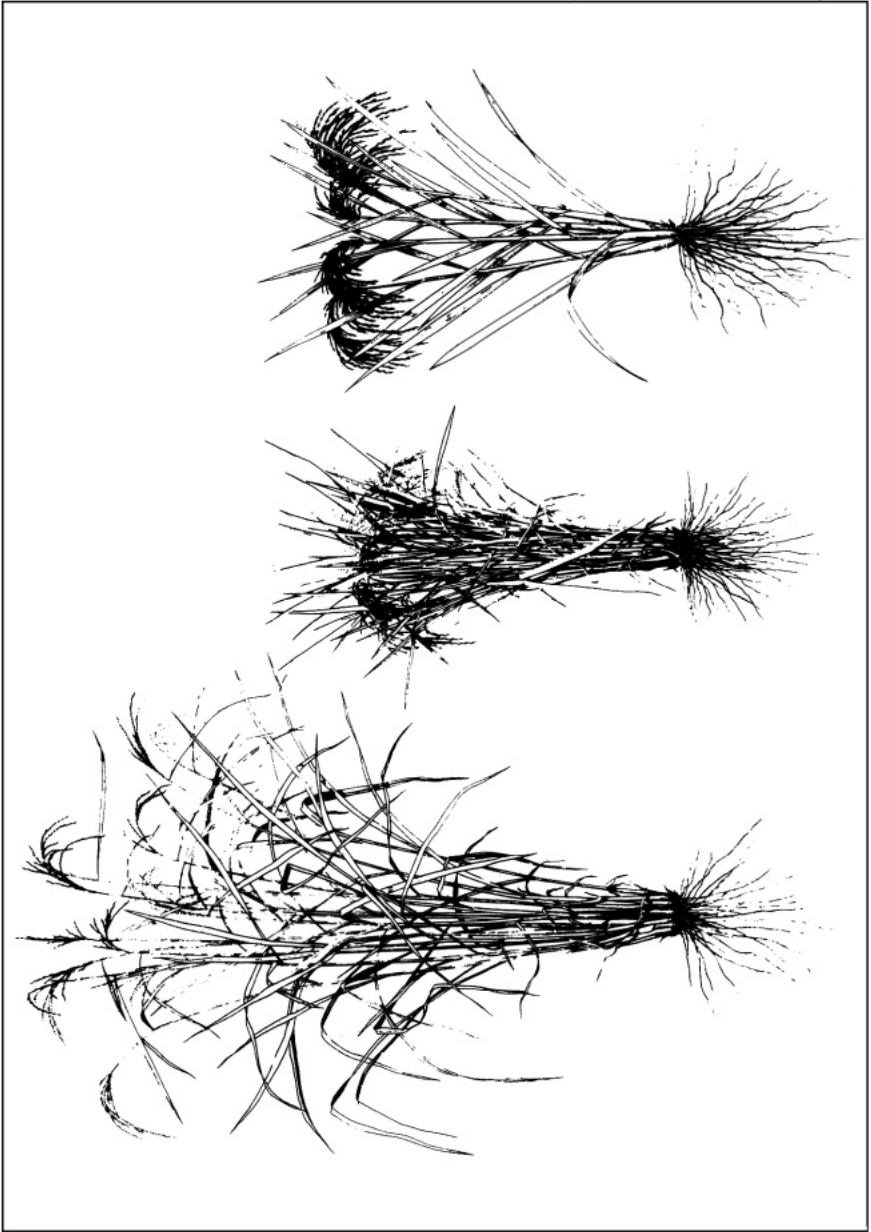
B. S. Vergara, B. Venkateswarlu, M. Janoria, J. K. Ahn, J. K. Kim, and R. M. Visperas

Rice yields during the last 20 yr have been greatly increased through varietal improvement and accompanying management practices. During the last decade, however, yields have apparently reached a plateau, and efforts to further improve yielding ability have not resulted in visible gains. A different plant type and accompanying changes focused on the production of more high-density (HD) grains are proposed. Studies at IRRI during the last 6 yr show the possibility of increasing grain yield potential by increasing the number of HD grains. The new plant type should be a low-tillering, panicle-weight type and have panicles with more primary branches, spikelets with large pedicellar vascular bundles, thick culms, medium-size grains, erect and thick leaves, dark green flag leaf sheath, slow senescence, high photosynthetic rate at low photosynthetically active radiation, medium growth duration, and intermediate height. The roles of environmental factors and cultural management on the production of HD grains are still being studied.

Rice yields in the tropics have been greatly increased during the last two decades, mainly through crop improvement and accompanying cultural practices. Use of IR8 and subsequent cultivars of similar plant type increased rice yields. However, yields in the last decade have apparently reached a plateau (Flinn et al 1982) and efforts to improve yielding ability have not resulted in visible gains.

Most efforts to raise the yield potential of the IR8 plant type have focused on increasing photosynthetic rates, biomass production, and harvest index (HI) (IRRI 1982). These have resulted in minimal gains (Vergara 1988a,b).

A different plant type with accompanying crop management changes focused on production of more high-density (HD) grains is proposed. The new plant type may be described in general as a low-tillering, panicle-weight type with a high percentage of HD grains (Fig. 1). Several different physiomorphological changes are needed to bring about effective grain filling, and accompanying cultural management practices have to be developed. These have been the subject of research at IRRI since 1984.



1. Traditional rice plant type, medium high-yielding variety plant type, and a plant prototype proposed for higher yield potential.

## High-density grains

The approach taken to improve grain yield is a change in plant type in order to increase weight per grain within a variety. Little research has been conducted along this line because workers have accepted the fact that the weight of a single grain is the most stable varietal character (Matsushima 1970), and variability within a variety is very small (Yoshida 1981). Studies have shown, however, that the weights of different grains within a variety are highly variable (Fig. 2). Grain yields of IR8 could possibly be increased by as much as 30% by improving the density of the filled spikelets. HD grains not only have higher volume and weight (Venkateswarlu et al 1986b), but also higher milling and head rice recovery (Venkateswarlu et al 1986a, Venkateswarlu and Vergara 1989) - a higher final market yield of rice. Mallik et al (1989e) found that using as seeds HD grains from cultivars with high HD grain index significantly increases rice grain yield. Intravarietal or intragenotype variation also is reduced with the use of HD grain seeds (Mallik et al 1990).

## Suggested plant type

To increase the number of HD grains, the following characteristics of a new plant type are suggested:

1. *Low tillering*, to produce vigorous and large tillers that result in more HD grains.
2. *Panicle-weight type*, to produce large panicles with mostly primary branches.
3. *Panicles composed mainly of primary branches*, since primary branches have mostly HD grains and fewer empty and half-filled spikelets.
4. *Large pedicellar vascular bundle*, for better transport of assimilates.
5. *Thick culm*, for more vascular bundles, less tendency to lodge, better support of panicle, and probably a larger area for carbohydrate accumulation.
6. *Medium-size grains*, since large grains have low density and usually are not completely filled.
7. *Erect and thick leaves*, for better light distribution and higher photosynthetic rate per unit leaf area.
8. *Dark green sheath* for the flag leaf, to increase assimilate production.
9. *Slow senescence*, for increased assimilate production and a longer grain-filling period.
10. *High photosynthetic rates* under low photosynthetically active radiation (PAR), so that carbohydrate supply will be less limiting during the wet season.
11. *Medium growth duration*, so that carbohydrates can accumulate before heading.
12. *Intermediate plant height* with an HI of 0.55, because semidwarf plants tend to be high tillering.

Currently available high-yielding varieties already have many of these traits. However, the traits need further evaluation and possible donors must be identified.



## **Low tillering**

Large tillers usually result in a higher sink:source ratio and higher spikelet number, percent filled spikelets, leaf area per tiller, and sink capacity (Choi and Kwon 1985). These result in more HD grains. To facilitate the production of large tillers, a low-tillering plant ideotype is needed. The IR8 ideotype is a high-tillering, panicle-number plant. Using denser planting to produce fewer tillers per hill in this ideotype will not result in heavy tillers, but rather in lightweight tillers with thin culms and small panicles.

A low-tiller-number ideotype would ensure a higher number of vascular bundles (Hayashi 1976) and a higher number of HD grains (Choi and Kwon 1985), and would facilitate the production of heavy tillers. Adoption of a low-tillering type would suggest using direct seeding to obtain optimum plant density. This aspect is very attractive, since there is a growing shift toward direct seeded rice in many rice-growing regions. The plant type described here is ideally suited for direct seeding.

Kim and Vergara (1989b) suggested that six tillers were optimal in the two cultivars studied. They reported that, in the high-tillering and relatively low-tillering varieties studied, the main culm followed by P2, P3, P1, P4, and S1P2 gave the highest panicle weights (Fig. 2). The other tillers gave highly variable and much lower yields. Using more varieties, Kim (unpubl. data) showed varietal differences in optimum tiller number (most likely, the optimum can be altered by nutrient levels and environmental conditions).

The number of vascular bundles is positively related to culm thickness, tiller order, and number of grains per panicle (Hayashi 1980). Secondary tillers have one less vascular bundle than do the primary tillers; tertiary tillers have two fewer vascular bundles (Hayashi 1976). Kim (1988) showed that the secondary tillers of the varieties he studied had not one, but two fewer vascular bundles than the primary tillers (Table 1). Although varietal differences may exist, this reduction in number of vascular bundles with order of tillering suggests that, if the aim is to have a high number of vascular bundles, a low-tillering plant type consisting mostly of early initiated or primary tillers is needed.

The HD grain index is usually higher in primary tillers than in secondary or tertiary tillers (Ahn 1986, Kim 1988).

## **Panicle-weight type**

To accommodate more primary branches on a panicle, a large panicle is needed. An increase in grain yield with improved management will result partly from an increase in weight per panicle or an increase in spikelet number. There was no significant decrease in HD grains with an increase in spikelet number per panicle in 886 varieties studied (Samantashinhar and Sahu 1986), indicating the possibility of aiming for a high HD grain index with large panicles.

**Table 1. Number of inner and outer vascular bundles in different tillers of IR25588 and IR58.<sup>a</sup> IRRI, 1987 DS.**

Tiller	IR25588		IR58	
	Inner vascular bundle (no.)	Outer vascular bundle (no.)	Inner vascular bundle (no.)	Outer vascular bundle (no.)
M <sup>b</sup>	24.4 ± 0.6	23.0 ± 1.0	22.0 ± 0.6	22.0 ± 0.4
P1 <sup>b</sup>	23.6 ± 0.6	24.2 ± 1.1	22.1 ± 0.7	21.8 ± 1.1
P2 <sup>b</sup>	23.2 ± 0.3	24.6 ± 1.2	22.2 ± 0.8	21.2 ± 0.7
P3 <sup>b</sup>	22.0 ± 0.4	23.8 ± 1.2	21.4 ± 0.4	20.2 ± 0.8
P4 <sup>b</sup>	21.2 ± 0.4	23.8 ± 0.9	21.0 ± 0.4	20.6 ± 0.6
P5	21.3 ± 0.4	21.0 ± 1.0	19.2 ± 0.9	19.6 ± 1.3
P6	18.0 ± 0.5	21.0 ± 1.2	18.2 ± 0.2	17.3 ± 1.1
S1P1	21.2 ± 0.7	22.8 ± 0.9	19.0 ± 0.7	18.8 ± 1.3
S2P1	20.4 ± 0.5	23.0 ± 1.0	18.6 ± 0.8	17.6 ± 1.1
S3P1	20.4 ± 0.6	20.8 ± 1.2	17.0 ± 0.8	18.0 ± 1.0
S1P2 <sup>b</sup>	21.2 ± 0.3	23.2 ± 0.9	20.4 ± 0.6	19.8 ± 0.3
S2P2	20.8 ± 0.4	22.2 ± 1.2	18.6 ± 0.9	18.6 ± 0.8
S3P2	20.0 ± 0.9	20.0 ± 1.0	18.0 ± 1.0	17.3 ± 1.7
S1P3	20.3 ± 0.6	20.3 ± 0.8	18.2 ± 1.0	18.2 ± 1.2
T1S1P1	18.6 ± 0.8	18.8 ± 0.4	15.0 ± 0.7	15.0 ± 0.5
T2S1P1	18.2 ± 0.9	18.7 ± 0.6	15.5 ± 0.2	15.0 ± 1.2

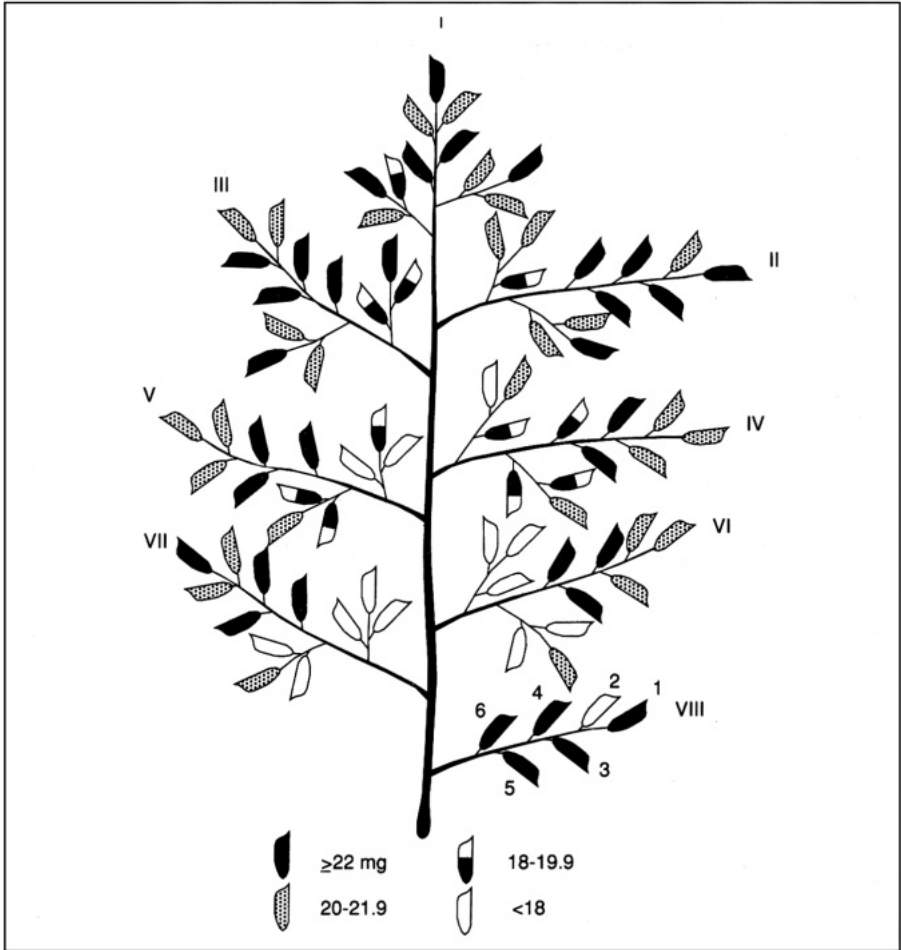
<sup>a</sup> Top six tillers. <sup>b</sup> Mean ± standard error.

### Panicles composed mainly of primary branches

Most of the HD grains are located on the primary branches of the panicle (Fig. 3). The importance of more primary branches and more spikelets on a branch for producing a higher number of HD grains has been reported by several workers (Ahn et al 1988b; Mallik et al 1988 b, c, e, 1989a,c,d; Venkateswarlu et al 1987a). Primary branches usually have fewer empty and half-filled spikelets. When the supply of assimilates was limited by defoliation, heavy weight grains formed on the primary branches and poorly filled grains on the secondary branches (Ahn and Vergara 1986). Ahn et al (1988a) reported that grains on secondary branches had lower rates of filling. Matsushima (1976) suggested that the number of secondary branches be reduced to raise the percentage of ripened grains.

The number of large vascular bundles in the peduncle is positively correlated with the number of primary branches (Dana et al 1969, Hayashi 1976, Joarder and Eunus 1980, Matsushima 1970). The number of vascular bundles is, in turn, related to the tiller order (Hayashi 1976); hence the suggestion for selecting rice plant types with mostly primary tillers.

Although the vascular bundles in all primary branches are similar, the first secondary branch develops better than the second secondary branch on the same primary branch (Ahn 1986, Chaudhry and Nagato 1970). This may partly explain the



3. Location of grains with different weights in a panicle of IR58 (Ahn 1986). Roman numerals indicate branch numbers, arabic numerals indicate spikelet numbers.

lower grain density on the secondary branches, and provides the rationale for not selecting varieties with many secondary branches on the panicle.

Panicles with more primary branches (or with a large number of vascular bundles) should be selected to compensate for the decrease in spikelet number with a decrease in secondary branches. The *Oryza glaberrimas* generally have a higher number of primary branches than do the *O. sativas*. They also have fewer secondary branches, where most of the low-density (LD) grains are located (Mallik et al 1989b,c).

Indica varieties have more vascular bundles than do japonica (Hayashi 1976). This characteristic shows up even in indica/japonica crosses, where the progenies have more and larger vascular bundles than do the japonica parents (Lee et al 1985).

The number of vascular bundles developed is also influenced by N nutrition (Lee et al 1985). This needs further study, as it would affect N fertilizer management practices in direct seeded rice.

### **Large pedicellar vascular bundle**

If the transport system is limiting, larger or more vascular bundles might enhance movement of assimilates. There is no direct evidence that the transport system is limiting. However, spikelets with HD grains have been reported to have bigger pedicellar vascular bundles (Ahn et al 1989), with a larger phloem area (Nishiyama 1983) and more, better developed vascular bundles (Chaudhry and Nagato 1970).

In wheat, Evans et al (1970) found a close proportionality between the phloem area in the peduncle and the maximum rate of assimilate import by the ear. However, they pointed out that this does not prove that the vascular system is limiting ear growth, since phloem development may be controlled by the ear through a feedback mechanism. Later experiments showed that half the vascular system in the peduncle may be severed without any reduction in the rate of accumulation of shoot assimilate in the ear (Wardlaw and Moncur 1976). Kim (unpubl. data) studied this phenomenon in rice and found little reduction in assimilate transport when the peduncle was partially cut 7 d after heading.

### **Thick culm**

With a larger panicle to support, a thick culm would be needed to decrease the probability of lodging. Thicker culms have more vascular bundles and a larger area in which to accumulate more carbohydrates.

### **Medium-size grains**

The occurrence of HD grains did not correlate with 1,000-grain weight within the range of 20.0 to 28.8 g (Venkateswarlu et al, unpubl.). This indicates that rice grains of relatively varying sizes can be developed while a high percentage of HD grains is maintained.

Grains >26.0 g have low density and are usually not completely filled (Takita 1986). In indica varieties, however, the occurrence of white belly (essentially, LD grain) is correlated positively with grain width (Takita 1986). Thus, coarse grains may tend to have lower grain density.

Smaller grains are also better adapted to overcoming the deficiencies in grain filling that result from environmental stress. At low PAR, large-grain varieties had lower weight for all their grains. In small-grain varieties, the grains on the secondary branches and lower branches decreased in weight but the rest remained constant (Kato 1986).

### **Erect and thick leaves**

The rationale for erect and thick leaves is similar to that discussed for modern plant type. Erect leaves provide better light distribution (Chandler 1969) and thick leaves have higher photosynthetic rate per unit leaf area (Yoshida 1972).

Although an erect leaf arrangement is especially valuable at flowering time, droopy leaves at early stages may be an advantage, to provide better light interception and weed control during the time plant canopy is sparse.

### **Dark green sheath for flag leaf**

The contribution to grain of the leaf sheath, especially that of the flag leaf, has not been adequately studied. The potential contribution and possible varietal differences need to be looked into. Preliminary studies by Janoria and Park (IRRI, pers. comm.) showed varietal differences in chlorophyll content and rate of senescence of the flag leaf sheath in rice. To improve HI and the canopy light environment, reduction in leaf area may be possible by improving the photosynthetic capacity of the leaf sheath.

### **Slow senescence**

Studies have not shown good correlation of leaf senescence with grain yield. Under temperate conditions, the leaf area at 30 d after heading is correlated positively with grain weight (Shin and Kwon 1985). With no mitigating factors, slow senescence should result in greater assimilates during the reproductive and ripening stages. The ineffectiveness of slow leaf senescence in improving grain yield may be due to the early senescence of spikelets or to a short grain-filling period, inadequate sink capacity, poor assimilate translocation, and other factors.

The need for balanced improvement of several traits simultaneously, not singly, may be the key to a better plant type. Increasing the photosynthetic rate and delaying senescence would be effective only if the auxiliary mechanism for filling and enlarging the sink is available.

### **High photosynthetic rates**

Although varietal differences in chlorophyll content (Kariya and Tsunoda 1980, Sasahara et al 1983, Yamakawa and Oshima 1977) and photosynthetic rates (Murata 1957, Murata and Iyama 1963) have been reported, their contribution to increased grain yield is not apparent (Yoshida 1972). Varietal improvements in rice through the years have shown no improvement in photosynthetic rates (Evans et al 1984). Accompanying changes, such as better translocation and partitioning of photosynthates, may be necessary for improved photosynthesis to be effective.

There is a need for improved photosynthetic rate at low PAR or during the monsoon season when assimilate supply is a limiting factor for higher grain yield (Singh et al 1968), and for morphophysiological changes to adjust to low PAR (Chonan 1967). Such useful traits should be exploited.

### **Medium growth duration**

Traditional varieties, with longer growth durations than high-yielding varieties (HYVs), accumulate carbohydrates in the culm before the reproductive stage (Vergara et al 1964). Accumulated carbohydrates would be useful in the production of larger panicles and heavier grains.

Accumulation of carbohydrates also is possible in medium-duration varieties that have a lag phase between maximum tillering and panicle initiation. The assimilates are used in the production of more tillers, but are also accumulated in the culm. The lag phase may be longer in a low-tillering type, where dense sowing results in an earlier maximum tillering stage (Janoria, unpubl. data; Dingkuhn et al 1990).

There are varieties, however, that accumulate carbohydrates in their culm, but little of the accumulation is translocated to the panicle. On the other hand, as much as 26% of grain weight may be contributed by carbohydrates from the culm (Cock and Yoshida 1972). The possibility of improving translocation of accumulated carbohydrate should be examined.

### **Intermediate plant height**

The main trait of HYV responsible for increased grain yields is reduced plant height and the subsequent increase in HI from less than 0.10 to 0.55 (Evans et al 1984, IRRI 1978). These changes resulted in less straw (less nonphotosynthesizing plant parts) and increased lodging resistance (Tanaka et al 1966). However, a further increase of HI, from 0.55 to 0.60, did not improve grain yields (Vergara 1988b).

An increase in biomass production without increased plant height, a change in HI of 0.55, or prolonged growth duration would be ideal.

### **Factors affecting high-density grains**

To further increase yield potential, several traits should be improved and incorporated into a total plant type. Improvement of a single trait may not result in any measurable yield increase. In determining the priority line of improvement, however, increasing the density of the grains was selected as the most rewarding trait on which to concentrate. Studies at IRRI for the last 6 yr have shown the possibility of increasing grain yield potential through an increase in the number of HD grains.

Several factors affect grain density. Our studies showed the following roles of factors influencing grain filling and density.

#### **Environmental factors**

*Drought.* Drought stress at anthesis and up to 20 d after anthesis greatly decreased the number of HD grains (N. Zapata, unpubl. data). The spikelets that produce HD grains are also those that produced HD grains under drought stress.

*Temperature.* Low temperature from after anthesis up to ripening favored the production of HD grains (Venkateswarlu et al, unpubl. data).

*Light intensity.* High PAR from flowering to harvest greatly increased the number of HD grains (Venkateswarlu et al 1987b). Shading of plants at anthesis drastically reduced grain yield. This is also reflected in the reduction of HD grains (Zapata, unpubl.).

*Planting season.* HD grain index was usually higher in the dry season than in the wet season (Kim 1988).

## Cultural management

*Nitrogen level.* Varieties differ in their response to N fertilizer. Several varieties showed an increase in HD grains with increased N from 0 to 250 kg/ha (Venkateswarlu et al, unpubl.). The increase was in spite of an increase in spikelets per panicle.

## Morphology

*Location of spikelets on the panicle.* Spikelets on the primary branches have a higher chance of being initiated and fertilized (Pateña and Vergara 1988). These spikelets also have higher grain density than those on the secondary branches (Ahn 1986). Spikelet numbers 5 and 6 on a primary branch are usually HD grains; spikelet number 2 usually has the lowest density or weight (Fig. 3).

*Vascular bundle size.* HD grains usually come from spikelets with large vascular bundles (Ahn 1986).

*Tiller order.* The first few tillers (6 to 8) usually produce more HD grains (Kim 1988, Kim and Vergara 1989a). They have more vascular bundles. The number of vascular bundles is  $n-2$  for primary,  $n-4$  for secondary, and  $n-6$  for tertiary tillers ( $n$  is the number of vascular bundles in the main culm). Thus, many secondary tillers and most tertiary tillers have fewer vascular bundles, smaller panicles, and in general, poor grain density. Number of primary branches and number of vascular bundles are correlated positively (Kim 1988).

*Primary branches.* Since HD grains are found mostly on the primary branches, panicles with more primary branches are recommended (Ahn 1986). Secondary branches have mostly LD grains, and their chances of being fertilized are low (Pateña and Vergara 1988).

*Grain size.* HD grains vary in weight from 20.0 to 28.0 g per 1,000 grains (Venkateswarlu et al, unpubl.). Yields with even higher grain weights usually have LD grains.

## Genetic factors

Very little research has been done on the genetics of grain density. Studies on hybrid rices and their parents show an increase in HD grain index in hybrid rice (Venkateswarlu et al 1986b). Grain density appears to be a genotypic character independent of grain size. The number of HD grains did not depend on the rate nor on the duration of grain filling (Venkateswarlu et al 1988). Venkateswarlu et al (1987c) found that all the vegetative growth durations they studied produced almost similar percentages of good grade grain. They concluded that it should be possible to combine the character of high number of HD grain with any vegetative growth duration. Mallik et al (1988a) found that multiple genes with opposite effects were involved. The dominance effect was 2-3 times higher than the additive effects, and the heritability estimate was more than 80%. Selecting for more HD grains may be effective in early segregating generations, such as  $F_3$  or  $F_4$ .

HD grains have beneficial effects in addition to increased grain yields. They result in better milling quality and more head rice. HD grain seeds have a higher germination percentage and better seedling growth, and produce more biomass than LD grains

(Arain 1990, Mallik et al 1988d). HD grains produce seedlings that recover faster after transplanting (expressed in tiller number and total dry matter production). HD grains result in more uniform, better crop establishment (Arain 1990).

A low-tillering plant prototype is being developed. A field study by Kim (1988) has shown a low-tillering plant type to be better adapted and to give higher grain yields than a high-tillering cultivar under direct seeding conditions. More field trials are needed, using plant types with greater variation in tillering capacity.

Incorporation of all the traits discussed here should lead to a higher grain yield potential for rice.

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Direct seeding practices in India

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In India, direct seeding is practiced for both irrigated and rainfed rice. In irrigated rice with good water management, yields average 3 t/ha or more; in rainfed rice, yields average only 0.8-1.2 t/ha. Intercropping direct seeded upland rice with a grain legume or other crop, intercropping deepwater rice with mungbean or sesamum, or intercropping a mixture of shortduration rices can increase net returns/ha. In submergence-prone rainfed rice, direct seeding helps in early stand establishment. In high-rainfall areas, direct seeded short-duration rice is followed by transplanted long-duration rice; in medium-rainfall areas, oilseeds and pulses are grown following rice. Yields are improved by line sowing. Chemical weed control, although effective under certain conditions, is not widely practiced. Direct seeded rice suffers from low fertilizer input, although response to fertilizer is evident. Current land use can be improved by introducing better adapted varieties, new cropping patterns, and integrated rice - fish farming in rainfed and deepwater areas. Policies to encourage adoption of improved direct seeding practices would result in increased productivity, profitability, and sustainability in both rainfed and irrigated rice farming.

Direct seeding is an ancient method of rice crop establishment in India, and is still a major practice, particularly in rainfed rice farms. Although transplanting is the dominant practice in irrigated rice, some farmers in most parts of India practice direct seeding (Table 1). The area under direct seeding probably will increase gradually, as social factors change and technologies are improved.

Traditional direct seeding practices in rainfed ecosystems (lowland, deepwater, and upland) include primitive shifting cultivation and settled cultivation.

## Direct seeding in Madhya Pradesh state

Direct seeded rice occupies 87% of the 3.71 million ha of rice in the Chhatisgarh region of Madhya Pradesh. Average yields are low, 0.8- 1.2 t/ha compared with 3 t/ha or more in irrigated transplanted areas with good water and nutrient management. Depending

**Table 1. Rice yields under direct seeding in rainfed and irrigated ecosystems.**

Land situation	Seeding practices	Average yield (t/ha)	
Upland	- rainfed	Dry seed broadcast	0.4 - 1.0
	- irrigated	Sprouted seed broadcast or line sown	0.4 - 5.0
Lowland	- rainfed	Dry seed broadcast	1.5 - 2.0
	- irrigated	Sprouted seed broadcast or line sown	2.0 - 3.5
Deepwater	- rainfed	Dry seed broadcast	1.0 - 1.5

on the land situation and soil regime, dry or sprouted seeds may be broadcast, dibbled, or drilled in lines. The areas under different seeding methods are given in Table 2 (Chandravanshi 1989).

In rainfed lowland fields, farmers choose different methods of direct seeding, depending on the onset of rain, soil moisture, and uniformity of rainfall (Chandravanshi 1989).

*Dryland seeding.* Dryland seeding is locally called *khurra*. The field is thoroughly plowed and dry seeds are broadcast without waiting for rain.

*Wetland seeding.* Wetland seeding is locally called *batar*. When the onset of rainfall is normal, farmers sow dry seeds on moist fields after 80-120 mm rainfall. Seeds are covered when the soil is leveled by laddering, using animal power.

*Lehi method.* When rain is continuous and dry seeding difficult, farmers broadcast sprouted seeds on puddled fields. This method is also called *muchuha*.

*Pinch method.* In the pinch method, seeds are mixed with a slurry of cattle manure (1: 10) and trampled. Coated seeds, either dry or as a seed-manure paste, are placed in pinches or broadcast on puddled fields. The coated seeds sink into the soil (Kerala Agricultural University 1987).

## Direct seeded rice in Orissa state

About 80% of wet season (kharif) rice in Orissa State is direct seeded. Farmers use modern varieties in puddled fields traditional, tall, photoperiod-sensitive varieties in rainfed lowland drought- and submergence-prone fields. Several of the traditional varieties possess drought tolerance at early growth stages and tolerance for temporary submergence, and are adapted to waterlogging. Weed management and maintaining optimum stand establishment are major concerns (Biswas 1988).

**Table 2. Distribution of rice area under different methods of rice culture in Chhattisgarh Region, Madhya Pradesh, India.**

Sowing method	Rice area (%)
Dry seeding on dry soil	27
Dry seeding on wet soil	50
Wet seeding on puddled soil	10
Transplanting	13

Rainfed rice farmers sow dry seeds; irrigated rice farmers sow dry seeds in dry plowed soil and sprouted seeds in puddled soil. Long-duration rice varieties are usually grown and fertilizer use is low, except where sprouted seeds are used in puddled lands and fields are irrigated.

*Beushaning or biasi.* Beushaning is used in dry seeded lowland fields to control weeds. But beushaning reduces not only the weed population, but also the rice plant population. Ricefields with 5-10 cm standing water accumulated from rains are sparsely plowed crosswise, rather shallow. The rice plants would be at the vegetative phase during beushaning, well before the vegetative lag phase of the traditional, long-duration varieties. During the beushaning operation, culms of the weed *Echinochloa* sp. (which resembles the rice plant at early growth stages but which develops internodes much earlier than long-duration rice) break and detach below the nodes. Rice plants escape this damage because nodal differentiation occurs later.

In studies on beushaning in traditional cultivar Safri-17 at Raipur, MadhyaPradesh, grain yield was highest when beushaning was done 45 d after sowing (Table 3) (Chandravanshi 1989).

Farmers usually do not fill gaps after beushaning, even though plant populations may be reduced. In an improved system, gaps are filled after beushaning operations.

In a comparison of beushaning after line sowing behind the plow and drill sowing without gap filling, drill sowing yielded 3.5 tha—at par with broadcast sowing with gap filling (Table 4). Beushaning in simple broadcast rice without gap filling produced

**Table 3. Average yield of rice in relation to beushaning. Raipur, Madhya Pradesh, India, 1979-80.**

Time of beushanling <sup>a</sup> (DAS)	Yield (t/ha)
25	2.8
35	2.9
45	3.3
55	2.6
Hand weeded twice	2.6

<sup>a</sup>DAS = days after sowing.

**Table 4. Plant population before and after beushaning and Safri-17 rice yield with different direct seeding methods in Madhya Pradesh, India.**

Sowing method	Rice population (m <sup>2</sup> )		Yield (t/ha)
	Before beushaning	After beushaning	
Broadcast (no gap filling)	222	133	2.8
Broadcast with gap filling	222	156	3.5
Drill sowing	201	159	3.5
Sowing behind plow	200	160	3.1

a low 2.8 t/ha (Chandravanshi 1989). Plots that were drill seeded or sown behind the plow without gap filling maintained better plant populations after beushaning (Chandravanshi 1989). In general, farmers broadcast seed or sow behind the plow.

All nitrogen applied basal or at beushaning was not as effective as split application at basal or at beushaning and at late tillering and panicle initiation. In studies with Safri-17, applying 30% N at sowing, 40% at beushaning, and 30% at late tillering was beneficial; applying 40% N at beushaning, 30% at late tillering, and 30% at panicle initiation stage gave similar yield (Table 5). The decision on when to apply N depends on field condition, soil type, and weather (Chandravanshi 1989).

### Direct seeding practices in upland ricefields

Upland rice accounts for 20% of the total rice area in India (Prasad and Tomar 1988), with nearly 85% of the upland rice in eastern India (Muralidharan et al 1988). Direct seeded traditional rice varieties perform well in the uplands, giving low but stable yields. Several new varieties developed through on-station research have been recommended, but they have not been widely used because fields have different growing conditions and different soil types (Prasad et al 1989).

**Table 5. Rice yield in relation to time of N application in beushaning systems, Raipur, India.**

Basal	Percent N applied <sup>a</sup>			Yield (t/ha)
	Beushaning	Late tillering	With irrigation at panicle initiation	
0	0	0	0	2.1
100	0	0	0	2.4
30	70	0	0	2.5
30	40	30	0	3.3
0	100	0	0	3.0
0	70	30	0	3.0
0	40	30	30	3.1
30	30	20	20	3.1

<sup>a</sup>Fertilizer: 40-13-16.6 kg NPK/ha. All P and K applied as basal. Variety was Safri-17.

**Table 6. Yield of improved short-duration rice varieties in direct seeded uplands, 1989 wet season.<sup>a</sup>**

Location	Variety	Yield (t/ha)
Faizabad, Uttar Pradesh	NDR118	3.0
Meru, Hazaribagh	RR165-825	3.1
CURRS, Hazaribagh	RR167-982	3.4
Urguttu, Ranchi	IET11432	4.0
Bhowanipatna, Orissa	DR92	3.3

<sup>a</sup> Source: EIRRRP 1989.

Rainfall is generally low and its distribution erratic. A direct seeded upland rice crop is likely to experience drought stress during critical growth phases (Prasad et al 1989). Research efforts are directed toward developing suitable short-duration varieties. Performance of improved varieties in farmer participatory research under improved management practices is given in Table 6 (ICAR-IRRI 1990).

*Intercropping and sequence cropping.* Upland rice may be grown as a single crop, be intercropped with grain legumes (i.e., green gram, black gram, red gram, cowpea, millet), or grown as a sequence crop with barley, gram, lentil, mustard, and linseed. Vegetables are grown in sequence with rice when farmers have access to irrigation. Cropping intensity varies in different upland areas. Yield and income from selected intercrops and sequence crops are given in Table 7 (Birsra Agricultural University 1990, ICAR-IRRI 1990).

**Table 7. Yield and economic return from intercrops in upland direct seeded rice at Hazaribagh and crop sequence at Kumarganj. <sup>a</sup>**

Crop	Yield (t/ha)	Gross income (Rs/ha)	Production CPST (Rs/ha)	Net return (Rs/ha)	Value: cost ratio
<i>Intercrop</i>					
Rice	1.6	314	2006	1138	1.57
Red gram	1.1	5400	687	4713	7.86
Total	2.7	8544	2693	5851	3.16
Rice	1.6	2898	2006	892	1.44
Green gram	0.4	1935	472	1463	4.10
Total	2.0	4833	2478	2355	1.95
Rice	1.6	2880	2006	874	1.43
Black gram	0.4	1620	472	1148	3.43
Total	2.0	4500	2478	2022	1.82
<i>Rice-based sequence</i>					
Rice	2.2	4210	2300	1910	1.80
Mustard	0.6	3200	1400	1800	2.30
Total	2.8	7410	3700	3710	2.00
Rice	2.2	4210	2300	1910	1.80
Lentil	1.0	4240	1500	2740	2.80
Total	3.2	8450	3800	4650	2.20
Rice	2.2	4210	2300	1910	1.80
Linseed	0.7	3450	1400	2050	2.50
Total	2.9	7660	3700	3900	2.10

<sup>a</sup>Source: EIRRRP 1989. \$1 = Rs 16.20.

*Direct seeding practices.* The traditional method of direct seeding in the uplands is to broadcast seed on plowed land, then level to cover the seeds. Some degree of soil compaction occurs. Row seeding has been reported to result in better weed control and stand establishment (ICAR 1987).

Farmers practice an indigenous method of row seeding: seeds are dropped into the furrow behind the plow, and covered by laddering. Table 8 shows the grain yields of varieties when this seeding method was combined with weed control (OUAT 1990).

Farmers may apply farmyard manure in dry seeded upland fields, depending on local availability. They use little chemical fertilizer, although response to fertilizer has been shown (Table 9).

## Direct seeding in deepwater ricefields

Direct seeding is the major practice in deepwater ricefields. Farmers usually broadcast dry seeds well in advance of monsoon rains. The vegetative growth phase is comparable with that of direct seeded upland rice. With the onset of the rains, deepwater fields are flooded, and rice plants grow in standing water for up to 3 mo, depending on depth and duration of water.

Rice varieties with drought tolerance at early growth stages and submergence tolerance during different growth phases are well adapted to deep water. Water depth and duration fluctuate during the cropping season. Long-duration, photoperiod-sensitive tall varieties are usually grown. Yields are low. During the last 15 yr, several

**Table 8. Grain yield of direct seeded upland DR92 rice with different methods of sowing and weed control practices at Bhowanipatna, Orissa, India, 1989.**

Treatment	Yield (t/ha)		
	Site 1	Site 2	Mean
Broadcast + hand weeding	2.5	2.6	2.51
Broadcast + 1 kg thiobencarb ai/ha	2.4	2.4	2.4
Behind plow sowing + hand weeding	2.9	2.9	2.9
Behind plow sowing + 1 kg thiobencarb ai/ha	2.8	2.8	2.8
Drilled + hand weeding	3.2	3.3	3.3
Drilled + 1 kg thiobencarb ai/ha	3.0	3.2	3.2

**Table 9. Yield of direct sown upland rice at different levels of fertilization. Bhowanipatna, Orissa, India, 1989.**

NPK fertilizer (kg/ha)	Yield (t/ha)	
	Red soil	Black soil
0-0-0	1.1	0.8
20-8-8-16.6	1.9	1.5
40-8-8-16.6	3.0	2.7
60-1 3-25	3.2	2.7

new varieties have been identified from on-station and on-farm research. Results indicate that new varieties have a yield potential of 4-5 t/ha, compared with 2-2.4 t/ha from traditional varieties (Table 10).

In submergence-prone rainfed lowland fields and in deepwater areas, farmers broadcast a mixture of short-duration and long-duration rices, usually in March-April, to minimize the risk of crop loss due to flood. Both varieties can be harvested when flooding occurs at the normal time. When flooding occurs early in the season, the short-duration variety will be lost (farmers may harvest mature grain of the short-duration variety from flooded fields; that grain is consumed soon after harvest). When flooding occurs late in the season, the long-duration varieties are affected (Table 11).

Usually traditional tall varieties with low yield potential (1.5-2.0 t/ha) are planted. The combined grain yield can exceed 3 t/ha when it is possible to harvest both short- and long-duration varieties with little flood damage. Research on ways to improve this farmers' practice has been limited.

Cropping intensity in direct seeded deepwater fields is low (Biswas 1988). Even so, farmers may grow several crops in sequence or as intercrops, or a second crop of irrigated rice, using tubewell irrigation source owned by the farmer or irrigation water purchased from neighboring farmers. At Pusa, Bihar, intercropping deepwater rice with sesamum, mungbean, or jute before onset of flooding gave a rice yield equivalent of 3.3, 4.2, and 5.0 t/ha, respectively; yield of deepwater rice as a sole crop was 2.2 t/ha (Rajendra Agricultural University 1990). Data on yield and economic return from

**Table 10. Yield of new deepwater rice genotypes<sup>a</sup> in on-farm trial at Gopainagar, West Bengal, India, 1989.**

Genotype	Yield (t/ha)			
	Site 1	Site 2	Site 3	Mean
CN570-652	4.8	4.8	5.4	5.0
CN570-570	4.6	4.6	5.8	5.0
CN705-18	4.6	4.8	5.2	4.8
Ausphal or Meghi	2.4	2.3	2.0	2.2

<sup>a</sup>Ausphal at site 1, Meghi at sites 2 and 3.

**Table 11. Grain yield of early (aus) and late (aman) rice crops, 1989 wet season, Eastern India.**

Treatment	Seed ratio <sup>a</sup> (early: late)	Yield (t/ha)
Early rice only		2.1
Late rice only		2.3
Early + late rice	1:1	3.1
Early + late rice	1:5:1	3.3
Early + late rice	2:1	3.3

<sup>a</sup> Seed rate = 75 kg/ha.

**Table 12. Yield and economic return<sup>a</sup> from rainfed lowland rice crop sequences in Masodha and Chinsurah, India, 1988-89.**

Location	Crop	Yield (t/ha)	Gross income (Rs/ha)	Production cost (Rs/ha)	Net return (Rs/ha)	Value: cost ratio
Masodha, U.P.	Rice	2.1	2280	2015	265	1.1
	Lentil	0.5	3100	1561	1539	2.0
	Rice	2.1	2280	2015	265	1.1
	Linseed	0.4	2450	1577	873	1.6
Chinsurah, West Bengal	Rice	1.8	3600	2000	1600	1.8
	Rice <sup>b</sup>	5.4	10800	5250	5550	2.1
Ghagharghat, U.P. I <sup>c</sup>	Rice	1.27	2540	2000	540	1.3
	Lentil	0.4	1900	950	950	2.0
	Rice	1.3	2540	2000	540	1.3
II	Lentil	0.5	2400	1170	1230	2.1

<sup>a</sup> US\$1 = Rs 16.20. <sup>b</sup> Transplanted rice in dry season. <sup>c</sup> I = lentil at normal seeding rate with no fertilizer; II = lentil with 50% higher seeding rate, and added N and P.

crop sequence studies using lentil, mustard, sesamum, and dry season rice commonly grown by farmers are given in Table 12.

## Conclusion

To improve direct seeded rice yield, research is needed

- To develop rice varieties of improved plant type suitable for upland, lowland, and deepwater areas, to replace low-yielding traditional varieties.
- To improve tillage practices for better land preparation to facilitate line sowing.
- To improve traditional cultural practices for soil, water, and weed management of rainfed farming systems.
- On sustainability issues of improved direct seeding technology for adoption by resource-poor farmers in rainfed areas.
- On component technologies for direct seeded rice.

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## Notes

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Research status and prospects of direct seeded rice in Korea

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Planting of rice in Korea is expected to change from hand and machine transplanting to direct seeding because of such socioeconomic changes as decreasing availability of farm labor, increasing farm wages, increasing mechanization, and production of rice beyond national self-sufficiency. These factors are encouraging development of labor-saving and cost-reducing production technology. In Korea, the optimal time for direct seeding on flooded soil is from late April to early May, when daily mean air temperatures are above 13 °C. The optimal seeding rate is about 30 kg/ha and the optimal seedling stand is 80-120 seedlings/m<sup>2</sup>. Coating rice seeds with calcium peroxide (CaO<sub>2</sub>) promotes seedling emergence in flooded soil. Japonica cultivars have higher germination rates and seedling emergence than tongil type (indica/japonica) cultivars because they have higher and faster uptake of dissolved oxygen under submergence. This suggests that a japonica cultivar has high oxygen utilization and/or low oxygen demand—ideal characters for the emergence of direct seeded rice on flooded soil. Applying N in splits at different leaf stages is desirable in direct seeding. Antilodging reagents have been effective. To control weeds in direct seeded rice, a combination of herbicides should be applied because the weed emergence period is longer.

Rapid economic growth has influenced the structure of agriculture in Korea. The farming population, 37.5% in 1975, dropped to 17.3% in 1988 and is expected to decrease much more. The gross national product per capita was only \$590 in 1975; it had increased to \$4,040 in 1988. The daily farm labor wage paralleled this increase.

Yields have increased from 3.8 t polished rice/ha in 1975 to 4.8 t/ha in 1988. Total rice production in 1988 was about 6 million metric tons, allowing self-sufficiency (Table 1). But increasing farm wages and decreasing availability of farm labor have resulted in much higher costs of production.

Rice production costs differ widely among countries. In 1987, the cost was \$464/t in Korea and \$225/t in the USA. The high production cost in Korea may be due to the small cultivated hectareage per farm household and to high labor costs. Labor cost is 58% of total production costs in Korea and only 9% in the USA (Lim and Park 1989).

**Table 1. Socioeconomic situation of rice production in Korea (Statistical Yearbook of Agriculture, Forestry & Fisheries 1989).**

	1975	1988
Total population ( $\times 10^3$ )	35,281	41,975
Farm population (%)	37.5	17.3
GNP (\$ per capita)	590	4,040
Daily farm wage (\$/person)	3.0	23.6
Rice production		
Cultivated area ( $\times 10^3$ ha)	1,218	1,260
Yield (t polished rice/ha)	3.9	4.8
Total production ( $\times 10^3$ t)	4,669	6,054
Production cost (\$/ha)	1,101	4,891
Net income (\$/ha)	1,281	5,953

Transplanting and harvesting require about 53% of the total labor input. About 66% of the total lowland area was machine transplanted in 1989, with mechanical harvesting. Even so, mechanization of agriculture in Korea is still far from that practiced in industrialized countries such as Japan and the USA. Park and Lee (1988) reported the manpower input for rice was 800 h/ha in Korea, 550 h/ha in Japan, and 20-30 h/ha in the USA.

## Climate

The Korean peninsula belongs to the temperate climate zone, with a climate characterized by hot and humid summers and severely cold winters. The annual mean air temperature is around 12°C, ranging from -10 to 30°C (Fig. 1). The temperature range is much greater in the north and the interior than in the south and along the coast.

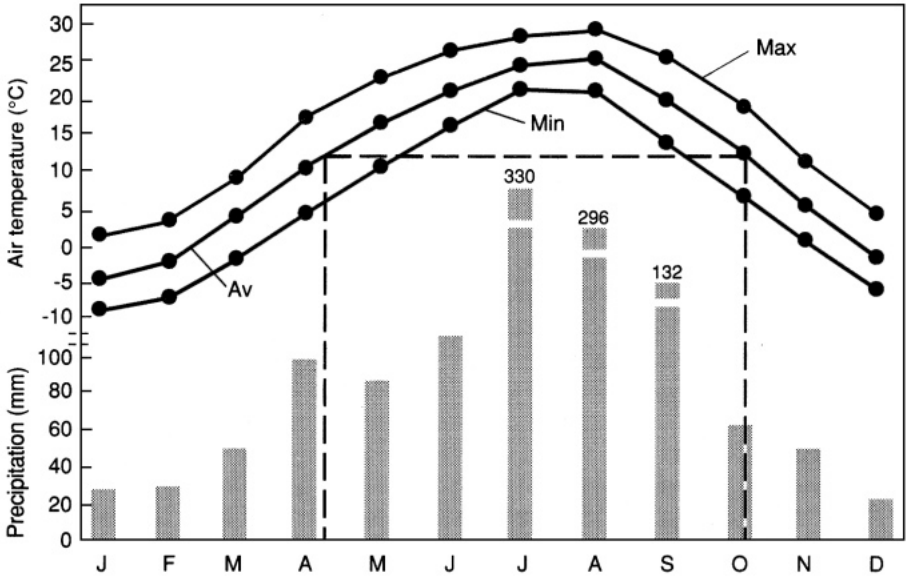
The rice cropping season is from April to October. Rice plants often suffer from cold damage at the seedling and maturing stages because of low temperatures, especially in the north and in the mountainous regions.

Annual precipitation averages 1,200 mm, with two-thirds of the total rainfall between July and September. The climate is more or less dry during transplanting and harvesting.

## Direct seeded rice adoption in farmers' fields

Until 1975, rice was direct seeded on around 20,000 ha, mainly in rainfed fields. By 1988, however, the area had declined to only about 3,000 ha. Direct seeding has not been widely practiced because of weather (low temperatures, extreme drought, and heavy rains), difficulties in achieving adequate seedling emergence and stand, extensive rat and bird damage, poor weed control, and lodging.

Direct seeding is also practiced in a reclaimed area of 10,000 ha in Seosan in the western coastal region. Airplanes are used to seed the crop. However, cultural practices differ with location, size of field, farmer management practices, and other factors.



1. Average of maximum, minimum, and mean temperature and precipitation in Suweon, Korea, 1964-89. The area bounded by dotted lines indicates the possible growth period of direct seeded rice in Korea.

### Changes in rice cultivation

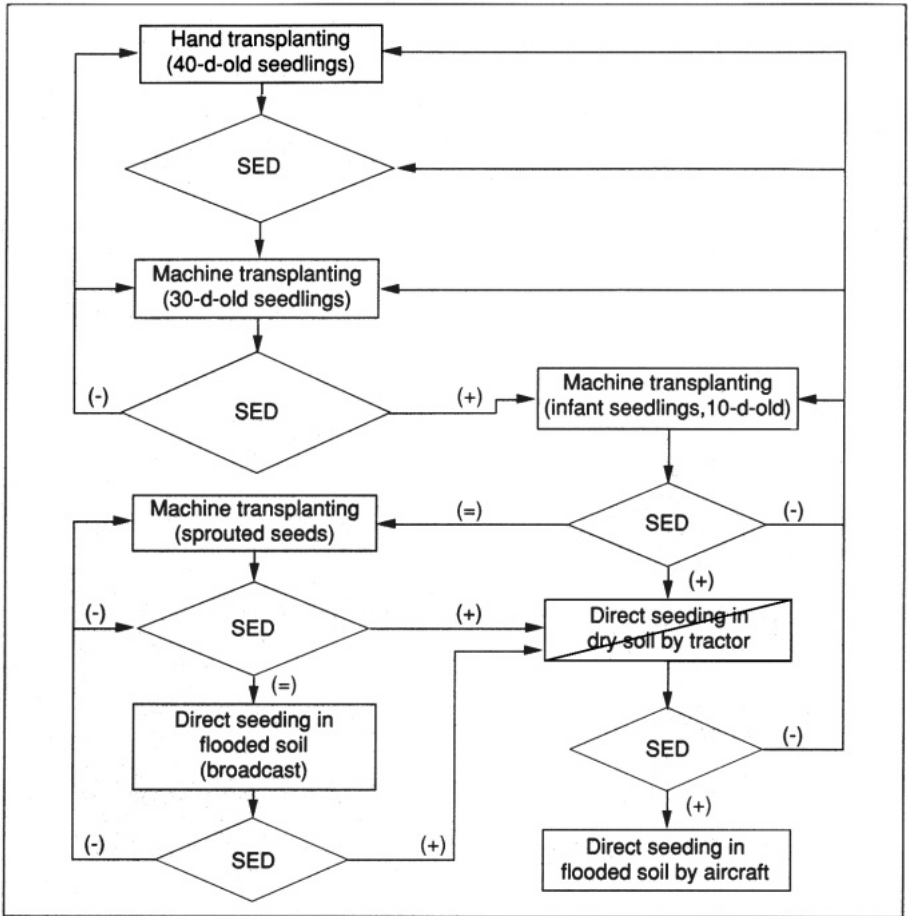
Lim and Park (1989) traced a developmental pattern for labor-saving and lower cost technology in rice culture in Korea (Fig. 2). Hand transplanting was replaced by machine transplanting with middle-aged seedlings (30 d old). A new practice is machine transplanting with infant seedlings (10 d old).

When the cultural technique using infant rice seedlings becomes widely adopted by farmers, the next pattern of rice culture will depend on socioeconomic development. The speed with which rice culture practices change, and the pattern of practices adopted will depend on the situation. If the socioeconomic situation improves rapidly, rice cultivation will change to direct seeding. If the situation is depressed, machine transplanting with sprouted seedlings will be advantageous. The final targets are direct seeding on dry soil by tractor and on flooded soil by airplane.

### Research on direct seeded rice

#### Seeding method

In Korea, direct seeded rice is sown on dry soil and on flooded soil. Direct seeding on flooded soil is of two types: broadcast seeding and drill seeding. No difference in grain yield was found with direct seeding methods (Table 2).



2. Schematic flow chart for possible changes of rice cultivation types according to socioeconomic development (SED) in Korea (Lim and Park 1989).

**Table 2. Seedling stand and polished rice yield as affected by different direct seeding methods (CES 1989).**

Soil condition	Seeding method	Seedling stand (%)	Yield <sup>a</sup> (t polished rice/ha)
Dry	Broadcast seeding followed by rototilling by power tiller	68	4.6 a
	Broadcast seeding followed by rototilling by tractor	70	4.7 a
	Drill seeding by machine	70	4.7 a
Flooded	Broadcast seeding on soil surface	76	4.8 a
	Drill seeding into 1 cm soil depth <sup>b</sup>	74	4.8 a

<sup>a</sup> Means did not significantly differ at the 5% level by DMRT. <sup>b</sup>The seeds were coated with CaO<sub>2</sub> to promote emergence.

Direct seeding on dry soil has long been a practice in areas where irrigation water is not sufficient. Rice seeds are directly sown on dry soil and the seedlings are managed like rainfed rice.

In recent years, a drill seeder attached to a tractor has been used to plant about 3 cm deep. This prevents lodging after heading. It takes about 6 hours to seed a hectare. When soil moisture is optimum, about 75% of the rice seedlings emerge 10-15 days after seeding. Weeds emerge before the rice seedlings, and weed control is a critical operation.

Broadcast seeding on the surface of flooded soil is common in places where the irrigation system is well developed or rainfall is sufficient. Critical daily air temperature for seeding is around 13 °C. After soil leveling, rice seeds are directly broadcast on the surface of the flooded soil. This can be done by hand, and is a suitable method for small farms. Rice seedlings emerge about 1 wk after seeding and the young seedlings are protected from birds and rats. After seedling stand establishment, water is drained to increase rooting activity and reduce lodging. Weed emergence is lower than in direct seeding on dry soil because the fields have been harrowed and flooded.

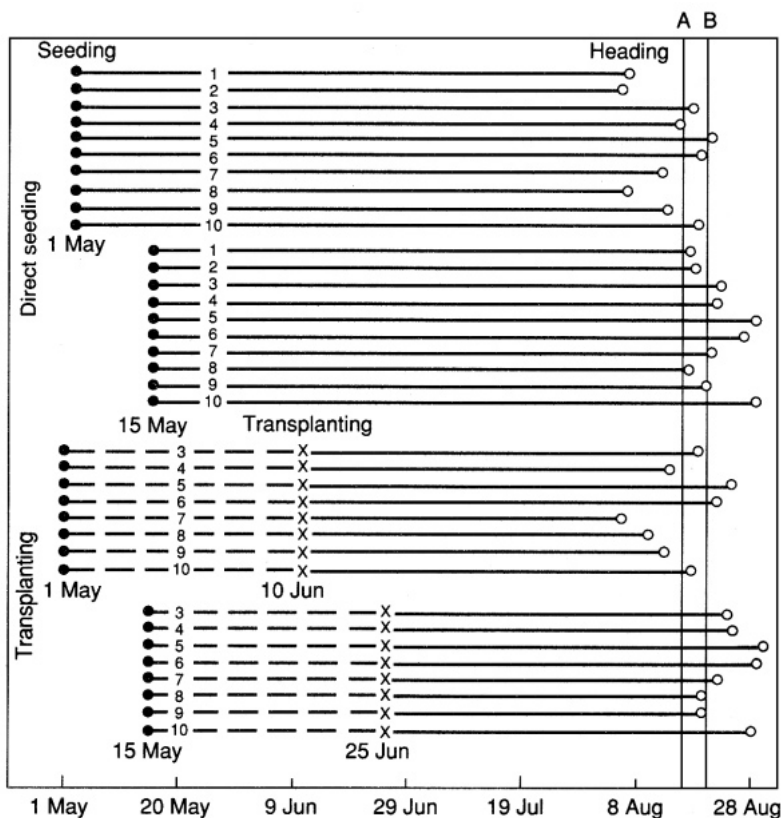
Drill seeding into flooded soil is an advanced method of seeding. Rice seeds are machine-drilled at 1 cm depth. This planting depth should reduce lodging. The rice seeds are coated with calcium peroxide ( $\text{CaO}_2$ ) to promote seedling emergence from muddy soil with a lower oxygen concentration. Calcium peroxide reacts with water to produce oxygen; the seedlings are able to take up the dissolved oxygen ( $\text{CaO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + 1/2 \text{O}_2$ ). This method of direct seeding may not become a viable option for farmers because it is difficult to coat seeds with  $\text{CaO}_2$ , a machine seeder is needed, and seeding is slow.

### Seeding time

Time of seeding is influenced, directly or indirectly, by temperature, the cold tolerance of the varieties used and their growth duration, and seeding method. In Korea, direct seeding begins when the daily mean air temperature is higher than 13-15 °C. In Suweon, in the middle part, rice can be sown from late April to early May (Fig. 3), with heading before 20 August to escape an early low temperature—a major cause of poor grain filling. In Milyang, in the southern part, the critical late heading date is 30 August, based on a cumulative ripening temperature of 760 °C for 40 d after heading (Fig. 4). The critical seeding dates are about 15 June for short-duration, about 10 June for medium-duration, and about 20 May for long-duration cultivars.

### Seeding rate

Factors that could determine the best seeding rate include direct seeding method, seed size and quality, seeding rate, and varietal duration. Seeding rate influences growth and yield of rice. Lee et al (1988) observed that the optimum seeding rate for broadcasting on flooded soil was 25-30 kg/ha (Table 3). At a seeding rate of more than 43 kg/ha, spikelets/m<sup>2</sup> was highest but percentage of ripened grain decreased, and grain yield was low.



3. Growth duration from seeding to heading in direct seeded and transplanted rice (CES 1985).

Japonica

1. Cheonmabyeo
2. Daeseongbyeo
3. Gihobyeo
4. Namyangbyeo
5. Nakdongbyeo
6. Akibare

Indica/japonica

7. Taebaekbyeo
8. Gayabyeo
9. Samgangbyeo
10. Pungsanbyeo

A = Threshold heading date for ripening in indica/japonica rice (15 Aug)

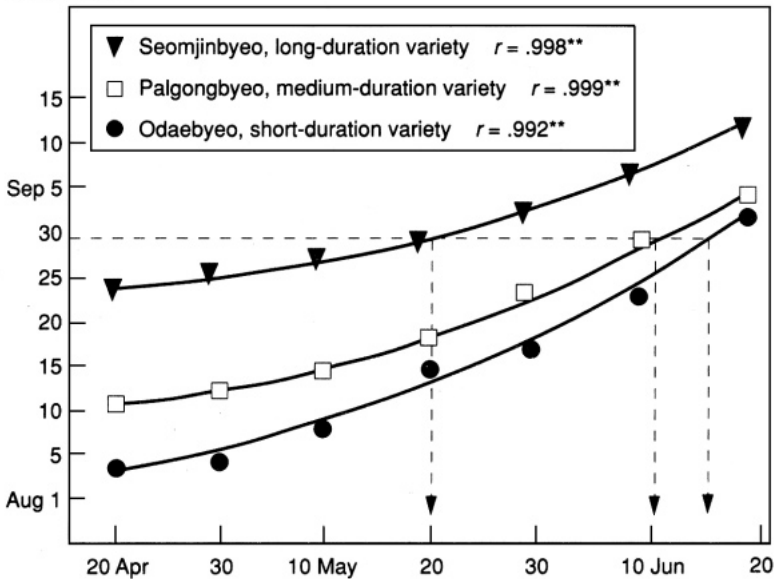
B = Threshold heading date for ripening in japonica rice (20 Aug)

For drilling on dry soil, 50 kg seed/ha was optimal (Park and Lee 1988). Lee et al (1988) obtained the highest yield from a stand of 80 seedlings/m<sup>2</sup> for a japonica-type variety and 120 seedlings/m<sup>2</sup> for a tongil-type (indica/japonica) variety.

### Germination

In direct seeded rice where seeds are sown on the surface of flooded soil or drilled at 1 cm depth, soil and water temperatures and oxygen supply are important factors for

#### Heading date



4. Feasible seeding date based on heading date in Milyang (YCES 1988). The arrows indicate marginal seeding date for direct seeded rice, based on a cumulative ripening temperature of 760 °C during 40 d after heading.

**Table 3. Yield and yield components as affected by seeding rate in direct seeded flooded rice<sup>a</sup> (Lee et al 1989).**

Seeding rate (kg/ha)	Seeding stand (no./m <sup>2</sup> )	panicles (no./m <sup>2</sup> )	Spikelets (no./panicle)	Ripened grain (%)	1000-grain weight (g)	Rough rice yield (t/ha)
16	30	333 d	78 ab	91 a	20.8	4.5 c
18	40	363 d	79 ab	89 ab	20.6	5.2 ab
21	60	365 d	80 a	90 a	22.0	5.4 a
27	80	419 c	79 ab	86 b	20.5	5.6 a
35	100	427 bc	69 ab	81 c	21.5	4.9 bc
40	120	470 ab	69 b	81 c	20.6	4.6 c
43	140	476 a	74 ab	78 d	20.8	4.6 c

<sup>a</sup>In a column, means followed by a common letter are not significantly different at the 5% level by DMAT. Seeding date = 5 May, variety = Nagdongbyeo (japonica type).

germination. Ota (1984) reported that coating rice seeds with CaO<sub>2</sub> as a germination stimulant promoted the emergence of rice seedlings.

Seedling emergence under submerged conditions of coated rice seeds differed with variety (Table 4). Japonica varieties had higher seedling emergence than tongil-type varieties up to 2 cm seeding depth. Tongil-type varieties showed poor seedling emergence even at 1 cm seeding depth (Park et al 1986).

**Table 4. Varietal differences in seedling emergence of direct seeded rice at 25 °C in flooded condition.<sup>a</sup>**

Cultivar	Seedling emergence (%) at given seeding depth		
	1 cm	2 cm	3 cm
<i>Japonica</i>			
Daeseongbyeo	55	53	3
Sobaekbyeo	38	25	10
Gihobyeo	63	43	3
Namyangbyeo	70	53	3
Akibare	65	68	8
Nakdongbyeo	60	35	8
Dongjinbyeo	65	23	0
Mean	59	43	5
<i>Tongil type</i>			
Taebaekbyeo	25	18	5
Gayabyeo	25	13	3
Samgangbyeo	15	15	0
Pungsanbyeo	8	5	0
Nampungbyeo	28	8	3
Mean	20	12	2

<sup>a</sup> Rice seeds were coated with CaO<sub>2</sub> 2 d before seeding.

Lee et al (1988) observed varietal differences in oxygen requirement for seed germination under water (Table 5). Dissolved oxygen uptake in japonica rice was higher and faster than in tongil-type rice. Germination in the japonicas was also much higher than in the tongil types. The coleoptile and the radicle in japonica varieties were longer than those in tongil types. These results suggest that a japonica cultivar with high oxygen utilization and/or low oxygen demand for germination and seedling emergence may be ideal for direct seeding on flooded soil.

### Fertilization method

Another method of applying nitrogen fertilizer is required in direct seeded rice because of its longer duration in the field compared with transplanted rice. When all the N is applied at seeding, N loss is higher at early growth stages, leading to lodging after heading. Split application is needed. When seed was drilled in dry soil, grain yield was higher with split application of 160 kg N/ha (Table 6). Split application based on leaf stage seems appropriate. However, fertilization method and the optimum N rate differ with cultivar, soil fertility, and location.

### Weed control

Weed control is one of the most critical factors for successful production of direct seeded rice because the soil is exposed during the initial growth stages of rice. Herbicide phytotoxicity also is more severe in direct seeded than in transplanted rice, and the herbicides used should be safe to rice seedlings. Because weed emergence spans a longer time in direct seeded rice, combinations of herbicides should be applied.

**Table 5. Varietal differences in germination percentage and dissolved oxygen (DO) uptake by rice seeds in 0,-saturated water (25 °C) (Lee et al 1988).**

Cultivar	Germination (%)	DO uptake (µg/grain per 3 d)
<i>Japonica</i>		
Sobaekbyeo	66.7	74.0
Daeseongbyeo	61.7	80.3
Gihobyeo	60.0	75.5
Namyangbyeo	81.7	81.4
Nakdongbyeo	75.0	93.4
Akibare	86.7	89.5
Mean	72.0	81.4
<i>Tonsil type</i>		
Taebaekbyeo	30.0	56.2
Gayabyeo	45.0	67.4
Samgangbyeo	40.0	63.1
Pungsanbyeo	23.3	57.9
Yongmunbyeo	38.3	51.3
Hangangchalbyeo	45.0	60.1
Mean	36.9	59.3

With broadcast seeding on the surface of flooded soil, weeds emerge about 30 d earlier than with transplanting, and young rice seedlings face severe competition with weeds. In an experiment with combined herbicide application, pyrazolate 2 d after seeding (DAS) with bentazon + quinclorac at 40 DAS and bensulfuron + mefenacet at 15 DAS with bentazon + quinclorac at 40 DAS gave excellent weed control without herbicidal phytotoxicity (Table 7).

With direct seeding on dry soil, weed emergence and the weed community are different, because the field is not flooded. Mefenacet at 3 DAS with bentazon + quinclorac at 50 DAS gave excellent weed control without decreasing seedling stand (Table 8).

**Table 6. Effect of applied nitrogen and split application on yield of drill seeded rice in dry Soil (YCES 1989).**

Basal	Split N application (%)						Milled rice yield <sup>b</sup> (t/ha)			
	5-leaf stage	7-leaf stage	PI <sup>a</sup>	Heading	80 kg N/ha	160 kg N/ha	240 kg N/ha	Mean		
20	-	20	-	20	-	20	4.6 <sub>a</sub>	4.9ab	4.9 <sub>a</sub>	4.8 <sub>a</sub>
20	-	30	-	20	-	20	4.4 <sub>a</sub>	5.1 <sub>a</sub>	5.0 <sub>a</sub>	4.8 <sub>a</sub>
30	-	20	-	20	-	20	4.3 <sub>a</sub>	4.8abc	4.9 <sub>a</sub>	4.7 <sub>a</sub>
40	-	10	-	20	-	20	4.3 <sub>a</sub>	4.5 <sub>c</sub>	4.7 <sub>a</sub>	4.5 <sub>b</sub>
50	-	0	-	20	-	20	4.2 <sub>a</sub>	4.6 <sub>c</sub>	4.7 <sub>a</sub>	4.5 <sub>b</sub>
				Mean			4.4	4.8	4.8	4.7

<sup>a</sup> Panicle initiation stage. <sup>b</sup> In a column, means followed by a common letter are not significantly different at the 5% level by DMRT.

**Table 7. Herbicide phytotoxicity, seedling stand, and weed control in rice broadcast on flooded soil (CES 1989).<sup>a</sup>**

Herbicides	Application rate (kg ai/ha)	Application time (DAS)	Phytotoxicity (0-9 scale)		Seedling stand (no./m <sup>2</sup> )	Weed control at heading (%)
			20 DAS	50 DAS		
Bensulfuron + mefenacet (G)	0.051 + 0.75	15	<1	0	90	68
Bensulfuron + mefenacet (G) fb bentazon + quinclorac (WP)	0.051 + 0.75 fb 1.2 + 0.3	15 fb 40	<1	0	90	97
Pyrazolate (G)	3	2	0	0	103	63
Pyrazolate (G) fb bentazon + quinclorac (Wp)	3 fb 1.2 + 0.3	2fb 40	0	0	103	93
Control			0	0	110	0

<sup>a</sup> DAS = days after seeding.

**Table 8. Herbicide phytotoxicity, seedling stand, and weed control in drill seeded rice in dry soil (CES 1989).**

Herbicides	Application rate (kg ai/ha)	Application time (DAS) <sup>a</sup>	Phytotoxicity <sup>b</sup> (0-9)		Seedling stand (no./m <sup>2</sup> )	Weed control at heading (%)
			20 DAT	50 DAT		
Mefenacet (Wp)	1.2	3	0	0	97	12
Mefenacet (Wp) fb bentazon + quinclorac (Wp)	1.2 fb 1.2 + 0.3	3 fb 50	0	0	97	96
Paraquat (Lq)	0.735	15	1-2	0	84	15
Paraquat (Lq) fb bentazon + quinclorac (Wp)	0.735 fb 1.2 + 0.3	15 fb 50	1-2	0	84	93
Control			0	0	97	0

<sup>a</sup>DAS = days after seeding. <sup>b</sup>DAT = days after treatment.

### Control of lodging

Plant lodging after heading greatly decreases grain yield. Lodging is more severe with broadcast seeding on the surface of flooded soil than with direct seeding on dry soil or drilling in flooded soil. Antilodging reagents were effective in reducing lodging of plants drill seeded into flooded soil, but not of those broadcast seeded on the surface of flooded soil (Table 9).

**Table 9. Effect of agrochemicals on lodging of direct seeded rice in flooded soil (CES 1989).**

Cultivation method	Chemical applied	Application rate (g ai/ha)	Culm length (cm)	Panicle length (cm)	Lodging (0-9 scale)	Brown rice yield (t/ha)
Broadcasting	Uniconazole (G)	1.2	74	18	5	5.1
	Paclbutrazol (Lq)	25.0	84	18	6	4.9
Drill seeding into flooded soil	No chemical control	-	89	19	9	4.7
	Uniconazole (G)	1.2	75	18	0	5.2
	Paclbutrazol (Lq)	25.0	82	18	0	5.3
	No chemical control	-	91	19	3	4.9

## Conclusion

Direct seeded rice might be the common cultural practice in the farmers' fields in Korea within 10 yr. For that to be successful, we need more detailed studies on variety, seeding rate related to seedling stand, fertilization, and weed and lodging control. Work also is needed on yield stabilization.

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## Notes

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Direct seeding practices for rice in Sri Lanka

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In Sri Lanka, rice is dry seeded in about 17% of the total annual rice area and wet seeded in 60%. The hydrology of the ecosystem and the soil type are the critical factors underlying establishment method. A bimodal rainfall seasonality greatly influences choice of variety (duration) and method of establishment. Dry seeded rice culture is common in the drought-prone rainfed lands of the dry and intermediate zones. Wet seeded rice culture is practiced in favorable rainfed lands, submergence-prone rainfed lands, and irrigated areas. Dry and wet seeding practices differ primarily in land preparation and crop establishment methods. At later stages, both crops are maintained under wetland conditions. Any deviation in the monsoonal rains affects dry seeded rice cultivation, resulting in drought stress at early or later growth stages. In submergence-prone lands, it may result in crop failure due to excess water. Land preparation for dry seeded rice does not permit good weed management. Uncertainty of water availability decreases farmers' use of fertilizer and reduces fertilizer efficiency in dry seeded rice. Traditional culture practices for direct seeded rice reflect how farmers have historically addressed their problems in rice farming.

From land preparation to crop and water management, the traditional practices followed by the rice farmers of Sri Lanka are unique. They have evolved over many years and have survived through several generations. Most of the traditional practices are scientific and meaningful (Jayawardena and Watabe 1984). This paper analyzes direct seeding practices in Sri Lanka and their significance to rice production, and discusses problems associated with these practices. It also focuses on the research needed on direct seeded rice culture, in view of its intensity and importance to the rice economy of the country.

## Production and demand for rice

Sri Lanka is rapidly reaching the stage where further expansion of the rice area will not be possible. In 1989, the total asweddumized area available for rice cultivation was 0.77 million ha (Table 1). Once river diversion schemes now planned are completed,

**Table 1. Total asweddurnized rice area in Sri Lanka, by administrative district, crop year 1989/90. <sup>a</sup>**

District	Area (x 10 <sup>3</sup> ha)			
	Major	Minor	Rainfed	Total
Colombo	-	1.13	6.36	7.50
Gampaha	2.30	2.80	12.62	17.72
Kalutara	0.67	3.05	18.48	22.21
Galle	-	-	23.92	23.92
Matara	3.65	6.00	11.73	21.38
Hambantota	20.92	5.80	1.69	28.59
Badulla	5.37	9.48	1.96	16.82
Moneragala	5.45	5.19	4.35	14.99
Walawe	14.38	-	-	14.38
Ratnapura	1.93	9.23	6.21	17.39
Kegalle	-	2.86	8.34	11.20
Kurunegala	14.77	35.79	29.25	79.82
Puttalam	6.60	10.03	3.62	20.26
Kandy	4.19	8.20	7.16	19.56
Matale	5.17	7.76	4.23	17.16
Nuwara Eliya	1.70	5.81	0.22	7.73
Anuradhapura	26.59	43.15	9.47	79.21
Polonnaruwa	31.10	2.25	1.97	35.32
Kalawewa	30.03	-	-	30.03
System "B"	10.68	-	-	10.68
System "C"	15.17	-	-	15.17
Jaffna	-	-	12.66	12.66
Killinochchi	11.17	0.62	11.75	23.55
Mannar	15.85	4.86	1.65	22.36
Vavuniya	4.35	10.73	5.08	20.17
Mullaitivu	5.26	3.10	9.25	17.61
Trincomalee	19.15	4.30	17.60	41.05
Batticaloa	18.70	2.75	35.65	57.12
Ampara	45.90	2.81	18.24	66.96
Sri Lanka	321.11	187.93	263.55	772.59

<sup>a</sup>Source: MAFC 1989.

the maximum area that will be available for rice will not exceed 0.8 million ha. If the present rate of cropping intensity (1.32 crops/year) continues, the annual area that will come under rice cultivation by 2000 will be about 1.0 million ha. About 82% of the total cultivated area ultimately contributes to national rice production.

The amount of rice needed for national self-sufficiency is highly debatable. Although rice is the staple food, its demand fluctuates with the price of wheat flour. If the price differential between wheat flour and rice is negligible, annual per capita consumption probably will continue to be 110-120 kg (Senadhira et al 1984). Given current consumption rates and the amount required for seed, and making allowance for wastage, etc., the annual production needed by 2000 is estimated to be about 4.1 million t (Table 2). To meet that requirement, the only option is to increase national average yields from today's 3.5 t/ha to 5 t/ha.

**Table 2. Estimates of rough rice requirements.**

Item	1980	1990	2000
Population (x 10 <sup>6</sup> )	14.40	17.00	20.00
Consumption (x 10 <sup>6</sup> t/year)	2.50	3.00	3.50
Seed requirement (x 10 <sup>6</sup> t/year)	0.08	0.09	0.10
Waste (x 10 <sup>6</sup> t/year)	0.20	0.30	0.50
Total (x 10 <sup>6</sup> t/year)	2.78	3.39	4.10

## Rice ecosystems

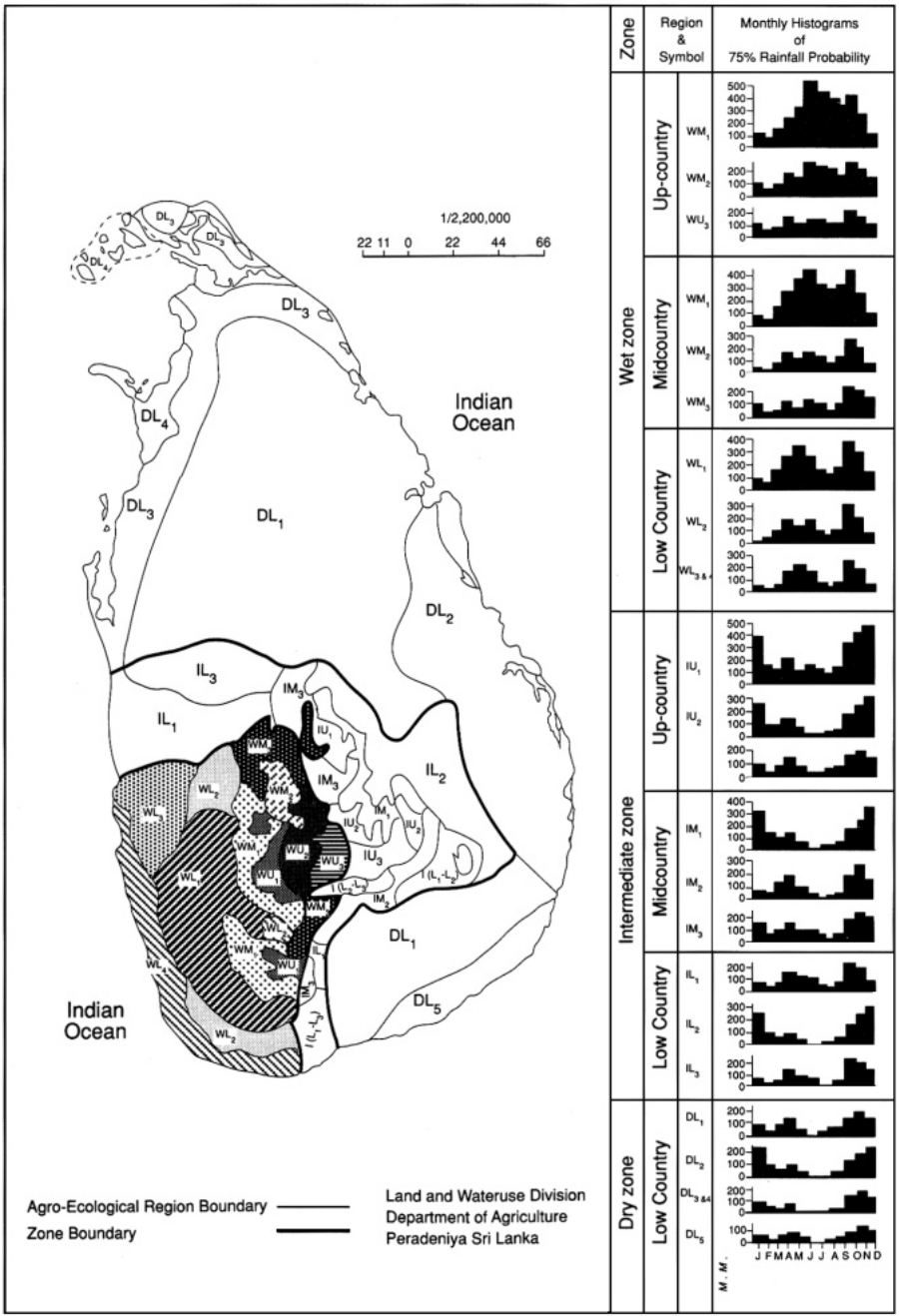
Sri Lanka's ricelands, which constitute about 771,000 ha (39%) of the 2,000,000-ha crop area, are mostly in the inland valleys and, to a limited extent, in the coastal plains, floodplains, and terraced slopes. Variable seasonal rains and a variety of soils, elevations, temperatures, and drainage patterns create complex and varying environments for rice production (Will 1989). Agroclimatic features are strongly influenced by the interaction of the two monsoons and the mountainous landmass in the south central area of the country.

Identifying climatic zones on the basis of annual rainfall into dry (900-1500 mm), intermediate (1500-2200 mm), and wet (>2200 mm) and on the basis of altitude into low country (<300 m), midcountry (300-1000 m), and up-country (>1000 m) allows categorizing ricelands into seven regions (Fig. 1). Panabokke and Kannangara (1975) classified the country into 24 agroecological regions according to altitude, rainfall and its distribution, major soil groups, elevation, temperature, and vegetation. Ricelands also were classified into three production systems—major schemes, minor schemes, and rainfed—based on the day-to-day management problems of irrigation systems. Will (1989) proposed a classification based on source, size, and method of water supply and usage, with tentative estimates of land area for each ecosystem (Table 3).

The cultivation year can be divided into two seasons, maha and yala. The seasons are very distinct in the dry zone, becoming increasingly less distinct toward the intermediate and wet zones. The northeast monsoon October to January is stronger and produces rain throughout the island. The southwest monsoon April to July provides rain mostly to the wet zone, the southwestern quarter, and the central highlands. As a result, moisture is sufficient year-round in the wet zone but dry spells are frequent in the dry and intermediate zones. Therefore, maha is the wet season for the dry and intermediate zones and yala the dry season. Cultivation during maha takes place between October and March, cultivation during yala is done between April and September.

### Rainfall distribution

The sowing-to-harvest duration of a rice crop in the different agroecological regions is primarily governed by rainfall seasonality and the resulting hydrology of the ricelands in various inland valley systems. Annual rainfall distribution, as shown by



1. Agroecological regions of Sri Lanka.

**Table 3. Classification of riceland based on source, size, and method of water supply and usage. <sup>a</sup>**

Type of riceland	Area (x 10 <sup>3</sup> ha)
1. Irrigated	
1.1. Major irrigation schemes	321.0
1.1.1. Tanks	242.1
1.1.2. Stream diversion	15.5
1.1.3. River diversion	63.4
1.2. Minor irrigation schemes	187.9
1.2.1. Tanks	126.1
1.2.2. Stream diversion	61.8
2. Rainfed	
2.1. Rainfed favorable (RF)	<i>b</i> 263.9
2.1.1. RF with supplementary irrigation	<i>b</i>
2.1.2. RF without supplementary irrigation	<i>b</i>
2.2. Rainfed unfavorable	
2.2.1. Drought prone	195.9
2.2.2. Submergence prone	16.0
2.2.3. Submergence and drought prone	6.0
Total	772.8

<sup>a</sup>Adapted from Will 1989 and MAFC 1989. <sup>b</sup>Area falling into this category not known.

rainfall probability histograms in the various agroecological regions, exhibits a distinct bimodal pattern (Fig. 1). Maha is the major rice-growing season, when approximately 90% of the rice area is cultivated. During yala, cultivation is confined primarily to the wet zone and to the major irrigation schemes in the dry and intermediate zones.

Any aberration in rainfall affects rice cultivation. In the wet zone, high precipitation during the early and late growth stages of the crop leads to crop failure. In the dry and intermediate zones, any deviation in rainfall affects the direct seeded rice crop and results in early-, mid-, or late-season drought stress.

### Significance of direct seeding

The rice crop establishment methods used by farmers are based primarily on the hydrology of the ecosystem (Table 4). Soil type and socioeconomic position also contribute considerably to the adoption of a particular establishment method.

In spite of continuous efforts by the Department of Agriculture to promote transplanting as the most suitable stand establishment method for irrigated and favorable rainfed environments, direct seeding appears to be the most common method used by rice farmers. As early as 1906, efforts were made to promote transplanting, but a survey in 1927 to investigate crop establishment methods adopted by farmers in three districts in the midcountry wet zone showed that only 2% of the rice area was transplanted; the rest was broadcast seeded (Amarasekera 1907 and Chandraratna 1950). Farmers acquired the technology needed for direct seeding, and understood its appropriateness for their rice ecosystem, a long time ago.

**Table 4. Crop establishment method in relation to rice environment and agroecological region.**

Ecosystem	Agroecological region <sup>a</sup>			Establishment method <sup>b</sup>			Cultivation
Major irrigation	D	I	W	TP	WS	–	–
Minor irrigation	D	I	W	TP	WS	DS	–
Rainfed (RF) favorable	–	–	W	TP	WS	–	–
RF drought	D	I	–	–	–	DS	Kekulan/ manawari
	–	I	–	–	WS	–	–
RF submergence	–	I	W	TP	WS	Mawee	–
RF drought and submergence	–	–	W	–	WS	DS	Deveredderi

<sup>a</sup>D, I, W=dry, intermediate, wetzones. <sup>b</sup>TP, WS, DS=transplanting, wetseeding, dryseeding.

The area under direct seeding has shown little variation. From 1976 to 1988, it ranged from 74 to 80% (Table 5,6). The area covered by irrigated lands exceeds 60% of the total area, making it clear that even in irrigated fields, most rice is direct seeded.

The importance of direct seeded rice culture is also reflected in its contribution to national rice production. In 1988-89, about 90% of national rice production came from the districts where direct seeding is practiced in more than half of the area.

### Direct seeding techniques

Direct seeding practices in the different rice environments vary a great deal. They can be broadly divided into wet seeding (broadcasting sprouted seeds on puddled soil) and dry seeding (broadcasting dry seeds on dry soil or on soil where moisture is below field capacity). The area under dry seeding is about 17%; that under wet seeding, about 60% of the total rice area. Row seeding on puddled soil is practiced in a very limited area.

### Wet seeded rice culture

Wet seeding is common in the wet zone and, to some extent, in irrigated lands in the dry and intermediate zones. The main feature common to wet seeding environments is puddling the soil before sowing sprouted seeds. Wetland tillage, the most common land preparation method, is used with both transplanting and wet seeding. The traditional method of tillage for lowland rice is plowing and puddling, primarily using cattle-drawn implements. In the major irrigation schemes, land preparation is done with tractor-drawn implements. Under some specific conditions, buffalo trampling and inversion by mammoities (hand hoes) are practiced.

*Plowing and harrowing with animalpower-drawn implements.* The most common land preparation method in the wet zone is plowing and harrowing with traditional animal-drawn implements (Jayawardena and Watabe 1984). The traditional plow is efficient only if the soil is wet but not inundated. In the first plowing, a country plow is used. After about a week, the second plowing is done at right angles to the first plowing. Then the field is inundated for about a week. Soil clods are broken down by a wooden harrow. About 10 buffalo days (5 pairs) are needed to plow one hectare.

**Table 5. Cultivated area ( $\times 10^3$  ha) under different crop establishment methods, 1976-88. <sup>a</sup>**

Year	Maha				Yala				Cultivated area			
	Direct seeding	Trans-planting	Total area	Direct seeding (%)	Direct seeding	Trans-planting	Total	Direct seeding (%)	Direct seeding	Total	Direct seeding	Direct seeding (%)
1976	343.15	100.10	443.25	77.4	198.40	41.71	240.12	82.6	683.37	541.56	79.2	
1977	420.78	122.12	542.90	77.5	219.85	61.58	281.44	78.1	824.34	640.63	77.7	
1978	414.64	142.84	557.48	74.4	163.42	55.77	219.20	74.6	776.68	578.07	74.4	
1979	345.32	147.54	492.87	70.1	207.63	43.44	251.08	82.7	743.95	552.96	74.3	
1980	424.11	142.81	566.93	74.8	209.40	54.59	263.99	79.3	830.92	633.51	76.2	
1981	497.06	125.13	622.19	79.9	206.58	54.59	261.17	79.1	874.48	703.64	80.5	
1982	371.21	134.61	505.83	73.4	212.11	54.21	266.32	79.6	772.15	583.32	75.5	
1983	462.83	150.18	613.02	75.5	195.62	40.94	236.56	82.7	849.59	658.46	77.5	
1984	473.48	112.19	585.68	80.8	310.96	81.53	392.49	79.2	978.17	784.45	80.2	
1985	437.18	147.40	584.59	74.8	248.56	69.35	317.91	78.2	902.50	685.74	76.0	
1986	418.53	146.41	564.95	74.1	264.63	69.22	333.85	79.3	898.80	683.16	76.0	
1987	396.21	131.41	527.63	75.1	216.06	45.60	261.67	82.6	789.30	612.28	77.6	
1988	436.47	126.37	562.85	77.5	261.76	65.79	327.56	79.9	890.41	698.23	78.4	

<sup>a</sup> Source: Division of Economics and Projects, Department of Agriculture, Sri Lanka.

**Table 6. Area ( $\times 10^3$  ha) under transplanting (TP) and direct seeding (DS) in different districts in Sri Lanka in crop year 1987-88.<sup>a</sup>**

District	Maha 1987-88			Yala 1988		
	TP	DS	DS (%)	TP	DS	DS (%)
Colombo	0.52	6.38	92	0.31	5.63	95
Gampaha	3.21	12.63	80	3.05	9.42	76
Kalutara	0.18	19.79	99	0.09	18.28	99
Galle	0.19	21.48	99	0.09	22.53	100
Matara	2.23	16.15	88	1.65	16.55	91
Ratnapura	3.97	12.47	76	3.10	11.75	79
Kegalle	7.20	4.25	37	5.60	4.08	42
Kurunegala	25.95	44.66	63	13.04	42.25	76
Puttalam	0.73	7.82	91	0.16	5.96	97
Kandy	17.90	1.15	6	12.25	2.02	14
Matale	7.78	7.37	49	2.42	3.06	56
Nuwara Eliya	6.82	0.15	2	3.54	0.06	2
Badulla	10.46	4.83	32	4.20	2.64	39
Moneragala	0.14	11.70	99	0.76	2.31	75
Jaffna	0.10	10.92	99	0	0	0
Killinochchi	0.51	21.10	98	0.25	1.80	88
Vavuniya	0.45	7.99	95	0	0.38	100
Mullaitivu	0.12	7.42	98	0	1.05	100
Mannar	5.53	10.53	66	0	0.91	100
Anuradhapura	2.39	44.75	95	0.18	8.86	98
Polonnaruwa	17.51	15.65	47	5.56	16.85	75
Trincomalee	1.38	11.87	90	0.04	8.57	100
Batticaloa	0.02	33.64	100	0.05	14.55	100
Kalawewa	4.57	24.04	84	0.39	5.03	93
Ampara	0.88	52.79	98	1.55	32.22	95
Hambantota	2.30	17.66	88	1.68	14.18	89
Sri Lanka	123.07	429.36	78	60.06	251.06	81

<sup>a</sup>Source: Division of Economics and Projects, Department of Agriculture, Sri Lanka.

*Buffalo trampling.* In the low country wet zone, hydrology and soil conditions in some ricefields do not permit using the plow or other implements, such as hand hoes. These fields are inundated or too moist, the plow line is invisible, and the soil is too sticky. Under these conditions, buffalo trampling appears to be the best form of land preparation. Farmers also prefer buffalo trampling as an efficient mechanism for weed control.

During trampling, the buffalo breaks up, macerates, and buries the weeds. Plowing only breaks up and covers the weeds, which then can recover more rapidly. Trampling is done once or twice, depending on field conditions and weed population (Jayawardena and Watabe 1984). About 15 buffalo days/ha are needed for a round of operation.

*Plowing with a tractor.* Tractor power for land preparation has become widespread. In 1988-89, tractors were used in more than 52% of the total rice area. A moldboard plow attached to a two-wheel tractor is used for the first plowing, and the field is then

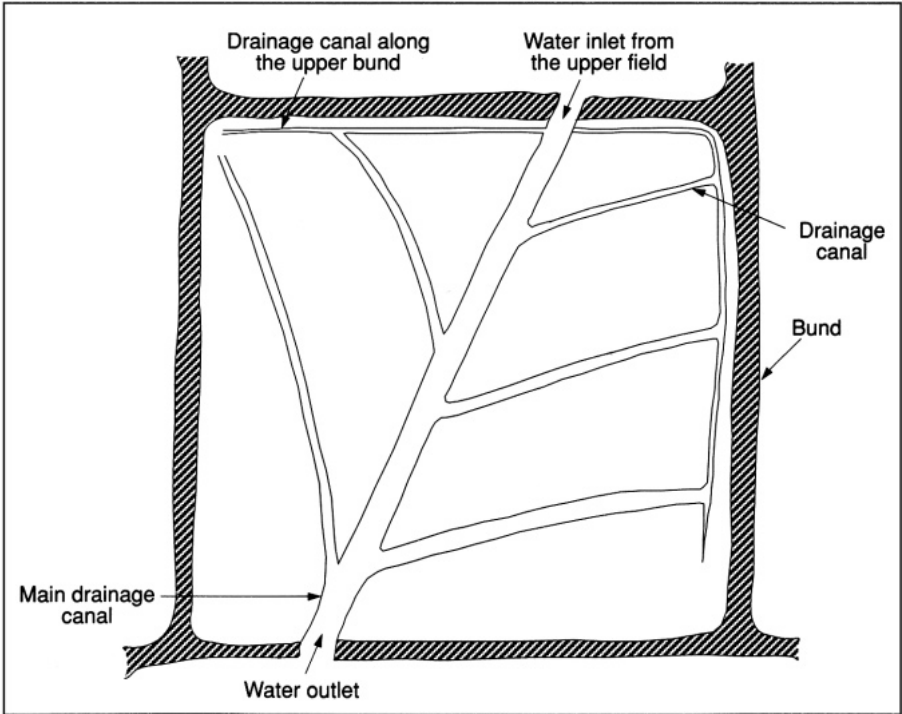
inundated. After a week, the second plowing is done using a rototiller. The rototiller is sometimes used for both plowings, depending on field conditions. Field leveling is done with a leveler attached to the tractor.

Four-wheel tractors are used for preparing large ricefields in the dry and intermediate zones. Four-wheel tractors with cage wheels and tyne tillers are used for the first and second plowing. Leveling is done by a leveler attached to the tractor.

*Land preparation by hoe.* In the upcountry wet zone, where terraced slopes are planted to rice, cattle-drawn implements cannot be accommodated. Farmers use a hoe to prepare the land. First and second tilling and breaking up of soil clods are separated by about a week of flooded condition.

Whatever method is used, the interval between initial land preparation and seeding is 3-4 wk.

*Leveling and drainage operations.* Leveling, the last stage of land preparation, is done to achieve good drainage. Leveled fields are divided into sections by small canals or furrows to ensure uniform drainage. These small drainage canals, made with a hoe and a small hand leveler, serve to distribute water uniformly during irrigation (Fig. 2). The farmers dig a small drainage canal just below the upper bund and parallel to each



2. View of a ricefield prepared for sowing sprouted seeds (adapted from Jayawardena and Watanabe 1984).

ricefield. This canal is connected to the main drainage canal and facilitates removal of toxic materials from the field. Scientific evidence has shown that this drainage canal helps ameliorate soil toxicity. The leveling and beautifully laid out system of irrigation and drainage canals in each bunded field reflect the high standard of craftsmanship developed by Sri Lankan rice farmers (Jayawardena and Watabe 1984).

*Seed sprouting.* Seeds are usually sprouted by soaking for 24-48 h and incubating for 48-72 h. Banana leaves are spread on the floor; soaked seeds are heaped in a 10-15 cm-thick compact layer, then covered with another layer of leaves; wet gunny bags are spread over the pile and weighted. This facilitates germination. Sometimes, both soaking and incubation take place inside a gunny bag. To drain off excess water, the gunny bag containing loosely packed seeds is placed on a small platform. The seeds in the bag are spread out in a 10- to 15-cm-thick compact layer and the wet bag covered with a dry bag. Weights increase pressure over the seeds. In some areas, farmers place a bag with loosely packed seeds alternately in and out of water for 12 h each for 3 d.

To slow down germination when land preparation is delayed, sprouted seeds are spread in a thin layer on the floor and allowed to dry in the shade, away from direct sunlight.

*Crop establishment.* Sprouted seeds are broadcast evenly by hand, at 100-150 kg/ha. Seeding rates of 250-300 kg/ha are not uncommon in areas where weeds are severe and land preparation is poor. Row seeding with seeders, using newly sprouted seeds is also practiced.

### **Dry seeded rice culture**

Dry seeding, popularly known as *kekulan* (Sinhala) or *manawari* (Tamil), is practiced in the drought-prone rainfed ricelands in the intermediate and dry zones. Land preparation can begin when the soil is dry or moist and, in anticipation of rain, is followed by broadcast of dry seeds onto unpuddled soil. Dry seeded rice can be subjected to alternate dry and wet spells, depending on rainfall occurrence and intensity. The main difference between dry seeded and wet seeded rice is in land preparation and seed establishment. When water is available, dry seeded rice becomes similar to wetland culture. The wetland condition depends largely on the quality of bunds—cultivation practices for dry seeding do not allow proper maintenance of bunds.

*Land preparation and seed establishment with country plow.* The country plow is used for land preparation after the first rains, when the soil is moist. The first plowing is followed by a second plowing 1-2 wk later, at right angles to the first plowing. At this stage, weeds are broken up, uprooted, collected, and removed from the field. Then dry seeds are broadcast onto the dry or moist soil. A third, light plowing is done crosswise to the second plowing to cover the seeds. In some areas, a wooden plow is used to slightly cover the seeds.

*Land preparation and seed establishment with tractors.* In northern Sri Lanka, where rice soils are sandy, tractors are used for land preparation. The initial, one-direction plowing is done with a disc plow or tyne tiller soon after harvest of the

preceding crop, and is deeper than the plowing that follows. The second operation with a tyne tiller is at right angles to the first operation. The third operation is done just before sowing.

Dry seeds are broadcast and a tyne tiller is run crosswise to cover the seeds (Poomampillai 1985). In some areas, a cattle-drawn country plow is used to cover seeds, when farmers feel that the tractor-drawn tyne tiller is too heavy and covering is too deep.

When a two-wheel tractor is used, a moldboard plow is used for the first plowing and a rototiller for the second plowing at right angles to the first. The rototiller is also used to cover the broadcast seeds. In some areas, a combination of cattle-drawn country plow and two-wheel tractor with rototiller is used. The first plowing is with the country plow.

This elaborate land preparation makes up nearly 25% of the total cost of rice cultivation, and not all the operations are necessary.

### **Fertilizer application**

Although most farmers know the importance of fertilizer in achieving the yield potential of improved rice varieties, very few apply the recommended rates in direct seeded rice, particularly in dry seeded rice. The risks involved in some direct seeded rice areas could be the reason.

The timing of fertilizer application also is determined by the economic status and educational level of the farmer. Farmers in submergence- and drought-prone areas are reluctant to apply fertilizer because of the uncertainty in the weather (unfavorable weather can delay fertilizer application). Because rice cultivation is limited to one season, and the fields are fertilized by floods, the need for inorganic fertilizer in the inland floodplains may not be severe.

There is no fertilizer recommendation for dry seeded rice culture. The wetland field condition is maintained with the rains and the wetland fertilizer recommendation is followed. Basal application is avoided or delayed until the rains come. Nitrogen is the most commonly used fertilizer.

In certain areas, organic matter in the form of dried leaves, dried cattle dung, compost, and other organic wastes is incorporated before sowing, to improve soil structure and fertility. Even in wet seeded rice, farmers add green leaves and other organic matter to the ricefields.

### **Weed management**

Yield losses due to weeds are higher in direct seeded rice than in transplanted rice, and weed management options are limited, especially for dry seeded rice.

Dry seeded rice is subjected to moist aerobic conditions and periodic flooding to variable depths during early crop growth. This favors competitive and diverse weed flora. In addition, the poor water control inherent in dry seeded culture reduces the efficiency of all weed control methods, particularly use of herbicides. In wet seeded rice, the land preparation method facilitates weed control.

Herbicides in combination with hand weeding is the common control practice in direct seeded rice. If sedges are abundant in lowland fields, some farmers place a banana trunk over the rice seedlings, to break the sedges and allow them to decompose.

### **Harvesting and threshing**

The availability of improved varieties with 90-135 d growth duration offers rice farmers the flexibility of more than 45 d in which to establish a crop to be harvested during the intermonsoonal dry spells—mid-February to mid- April for the maha season and August for the yala season. In general, farmers do not use a standard criterion to decide the optimum time for harvesting, and there is a tendency for the crop to be overmature before it is harvested. This leads to grain losses due to shattering, exposure of stored grain to field pests, and deterioration of grain quality. Direct seeded rice also is more prone to lodging during the intermonsoonal thunderstorms, with heavy yield losses.

Harvesting is mostly manual, with the use of sickles. The usual practice is to cut the straw about 30 cm above the ground level. Farmers clean a portion of a field or an upland area close to the field as a threshing floor. A threshing floor is used by a community of farmers. The traditional practice is to heap harvest at the center of the floor and allow 4-6 buffalo to trample it. With the current shortage of grazing lands, the trend now is to use tractors or mechanical threshers.

Some farmers in the dry zone systematically heap the harvest in the field for some time before threshing.

### **Problems associated with direct seeded rice**

Even though transplanting results in better crop management and higher yields, farmers continue to use direct seeding for other reasons. In many rice-growing environments and situations, direct seeding appears to be more suitable.

Transplanting is time-fixed. A farmer must organize his activities at least 4-5 wk before transplanting. Even farmers in major irrigation schemes, with an assured supply of water, prefer wet sowing, mainly because of the shortage of manpower and/or the high cost of labor. The practice of direct seeding under these situations should be viewed from a socioeconomic perspective.

In the rainfed favorable lands, the reason for direct seeding relates to a variety of environmental features in the ecosystem. In the rainfed unfavorable (drought-prone) lands, environmental features are such that dry seed establishment could be the only option available.

### **Stand establishment**

In direct seeding, the most difficult problem is establishing a uniform crop stand. With wet seeding, a crop stand may be poor if leveling is not properly done or if heavy rains follow sowing. Bird damage also is a major cause of poor stand establishment. In dry

seeded rice, a crop stand reflects the skills and efforts of the farmer in land preparation and in broadcasting dry seeds. The crop stand is greatly affected if seeds are placed too deep. A prolonged period of heavy rains or drought following sowing affects seed germination and seedling survival.

In some areas, especially in the eastern region, farmers sow four times more seeds than are used in other areas to establish a good stand and to control weeds.

### **Weeds**

Weeds are the main biological stress in direct seeded rice. This is due partly to poor land preparation and crop stand and partly to the difficulty of weed control in a direct seeded field; it could also be an inherent defect in the traditional practices used. Preemergence or postemergence selective herbicides are the only workable solution, and only farmers with higher economic means can afford chemicals to control weeds at the proper time. In dry seeded rice, land preparation does not serve as a weed control method as it does in wet seeded rice. Bund management also is not properly done in dry seeded rice, and the weed problem is more severe.

### **Insects and diseases**

Dry seeded rice is more prone to seedling blast. When environmental conditions are conducive, the disease spreads rapidly and causes severe damage. Rice yellow stem borer and thrips are more prevalent in dry seeded rice. Insect and disease problems associated with wet seeded rice are similar to those found in transplanted rice. However, pest control operations (like spraying) are very difficult in direct seeded crops, especially when plant density is very high. The protection expected from pesticide application cannot be achieved, and multiple applications sometimes are needed for adequate control.

### **Rice varieties**

Improved, short-statured, erect-leaf varieties could be accommodated in wet seeded rice culture. But because they are poor weed competitors, they are not suitable as dry seeded rice. Farmers are using tall, older improved varieties that are lower yielding and blast susceptible. High-potential, disease-resistant varieties are needed for dry seeded rice.

### **Rainfall**

Wet season rice cultivation starts with the July rains, and final operations may last from late August to sometime in October. Land preparation in the northern part of the dry zone is early. In maha, when the rains are concentrated from October to December, and in the dry zone, the seedling stage of early crops or the reproductive or maturity stages of late crops of dry seeded rice face the risk of drought. In the intermediate zone, dry seeded cultivation begins with the first northeast monsoon rain, in mid-September for the maha season and late April or early May for the yala season.

## Future needs of direct seeded rice

To improve the productivity and profitability of direct seeded rice, research is needed on varietal improvement and technology development. Varieties for direct seeding should possess good seedling vigor, deep roots, and weed competitiveness. Tolerance for drought and submergence and resistance to thrips and blast also are needed. Incorporation of nonlodging characteristics should be given priority. A unicum plant could be an advantage in improving direct seeded rice.

Research on technology development should be directed toward improving seeding rates, fertilizer and weed management, and pest and disease control. A system for rainfall prediction is needed to guide farmers in making management decisions. An effective crop insurance scheme should also be initiated.

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## Notes

*Acknowledgment:* Dr. S. D. G. Jayawardena, head, Plant Genetic Resources Centre, Gannoruwa, contributed helpful comments in the preparation of the manuscript.

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Direct seeded rice in the temperate climates of Australia, Italy, and the United States

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Rice in temperate climate Australia, Europe, and the United States, in contrast to that in the tropics, is limited to only one crop a year. In the southernmost, subtropical climates of the United States Gulf Coast region, rice may be ratooned for a second harvest. Rice seedbeds are prepared dry and nearly all the hectareage is direct seeded. The crop is entirely irrigated. The climate is characterized by long days, high solar radiation, and relatively large diurnal temperature fluctuations. Soils are high in clay or, if medium textured, underlain with impermeable hardpans or claypans. Water losses through deep percolation are minimal. Field size varies by country, from 5 ha in Italy to as much as 40 ha in Australia and the United States. Rice culture is highly mechanized, requiring as little as 7-10 labor h/ha in some regions. Yields range from 5.8 t/ha in Italy to 8 t/ha in Australia. The highest yields on a regional basis have been recorded in California, where an average 8.8 t/ha were harvested on 164,000 ha in 1989.

Compared to its culture in Asia, rice culture in southern Europe, the United States, and Australia has a relatively short history. Rice was introduced into Italy during the fourteenth and fifteenth centuries. In the United States, rice was first produced commercially in the middle of the eighteenth century; in Australia, rice was first produced in the twentieth century (Willson 1979, Wright et al 1989). In Italy, rice was hand seeded until transplanting was introduced in the early 1900s. By 1960, 50% of Italian rice was transplanted. But with increasing costs for human labor, mechanized direct seeding replaced transplanting and by 1989 accounted for 98% of Italian rice hectareage.

Commercial rice production in Australia and the United States paralleled the general mechanization of agriculture in industrialized countries, and labor-intensive methods of stand establishment (such as transplanting) were never commercially accepted. All riceland in these countries is mechanically direct seeded. In the United States, for example, the labor required to cultivate and harvest 1 ha of rice is less than 17 h/crop. In Asia, more than 600 labor h/ha may be required, often in a rice crop that produces much lower yield (Rutger and Brandon 1981).

## Location and climate

Rice is produced from 34° to 36° south latitude in temperate Australia, and at 45° north latitude in Italy. In the United States, rice is grown in three major areas: the Grand Prairie and Mississippi River delta of Arkansas and Louisiana from 32° to 36° north latitude, the Gulf Coast areas of Louisiana and Texas from 29° to 31° north latitude, and in California from 38° to 40° north latitude (Table 1).

The climate varies from semiarid California, USA, where less than 50 mm rainfall occurs during the growing season, to the humid subtropical Gulf Coast, USA, where rainfall may total 700 mm. A rice crop may be produced in 120 d in subtropical regions, but require as long as 180 d in New South Wales, Australia. In the more northern latitudes, summer days are long and solar radiation is high, but large diurnal fluctuations in temperature occur. Considerable research is focused on development of cold-tolerant cultivars and management strategies to avoid low-temperature stress in the more extreme latitudes.

## Land grading, irrigation, and drainage

Level land formation is essential to good irrigation practices regardless of field size, but it is especially important on the large fields of Australia and the United States. Leveling allows water drainage in dry-seeded rice and the maintenance of a uniform water depth that facilitates stand establishment in water-seeded rice. Rapid drainage and reflooding may be needed to control pests and abiotic disorders, and thorough drainage is needed at harvest. Leveling also improves the efficiency of irrigation management and water use. Considerable hectarage has been leveled with laser-directed equipment. The development of laser technology for improved water manage-

**Table 1. Location, rainfall, and growing season of rice in Australia, Italy, and the United States.**

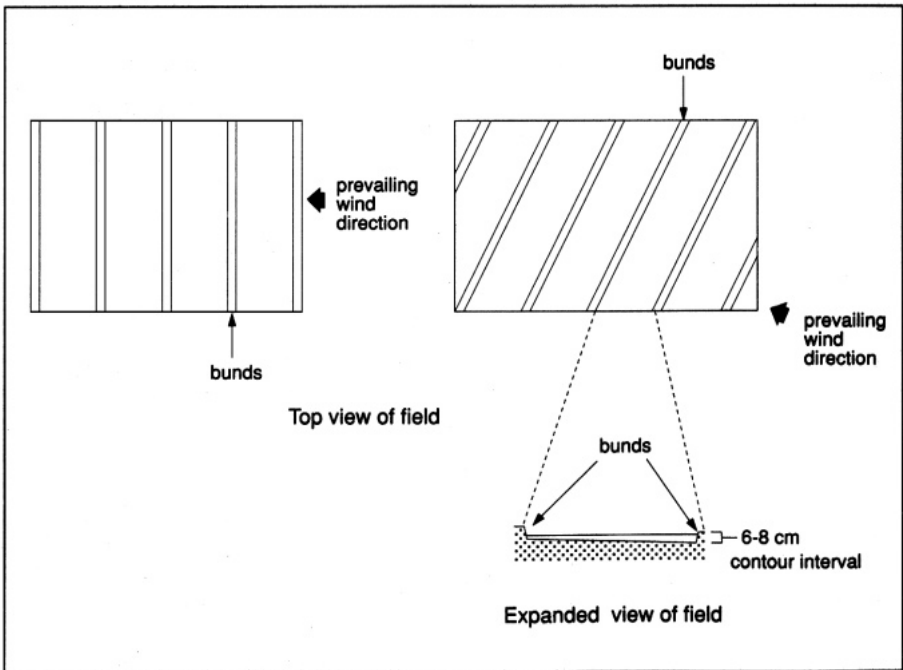
Location	Latitude (range)	Rainfall during season (mm)	Rice growing season	Direct seeded (%)
Australia				
New South Wales	34 - 35° S	289	Oct - May	100
Italy				
Milan	45° N	450	15 Apr - 15 Oct	98
United States				
Arkansas	33 - 36° N	700	1 Apr - 20 Oct	100
California	38 - 39° N	<50	1 May - 15 Oct	
Florida	27° N	1,000	15 Feb - 30 Oct	
Louisiana	31 - 33° N	650	24 Mar - 15 Sep	
Mississippi	32 - 35° N	635	1 Apr - 30 Oct	
Missouri	36 - 38° N	500	15 Apr - 15 Oct	
Texas	28 - 30° N	550	1 Apr - 30 Sep	

ment has been credited as second only to the introduction of semidwarf varieties in contributing to the increased yields in California during the 1980s.

Before laser leveling technology was developed, curved levees (bunds) were formed along the natural topographical contours of the land. Increasingly, rectangular areas of even slope are being constructed using laser-directed landforming equipment (Fig.1). The rectangles, called bays in Australia and checks in California, require fewer levees and increase the efficiency of farm machinery.

The slope established in a field depends largely on the rice-based cropping system. In rice-only systems, the land may be leveled to a slope of 0.02 to 0.05 m/100 m. In rice-row crop systems, grades of 0.1 to 0.2 m/100 m are needed to provide an adequate slope for irrigating and draining the rotation crop (University of California 1983, Wright et al 1989). Overly steep slopes make the control of water depth virtually impossible. Leveling to zero grade for rice-only systems provides the most precise control of water depth. However, complete surface drainage during stand establishment or for harvest is extremely difficult on completely flat fields.

In Australia and the United States, contour levees capable of retaining 40 cm or more water are placed at vertical intervals every 5-8 cm of elevation. The size of the bays and



1. Diagram showing smaller (2-6 ha) areas (bays or checks) defined by levees or bunds in large (up to 80 ha) fields in Australia and the United States. The levees are constructed at every 5-8 cm drop in elevation, in relation to the slope of the field and the prevailing wind direction.

checks is commonly 2-6 ha, depending on the slope, but rarely exceeds 8 ha because of the potential wind and wave damage to young rice seedlings in large open water expanses (University of California 1983, Wright et al 1989).

In Australia, Italy, and some regions of the United States, irrigation water is supplied through a complex network of channels coupled to natural surface water. This water originates from rainfed and snowfed catchments in nearby mountains, is supplemented with groundwater, and is excellent for rice. In some regions of the United States, irrigation is exclusively from pumped groundwater.

Drainage canals are necessary to remove water from ricefields. That water is frequently reused, flowing from upstream drainage canals into downstream irrigation supplies for reuse in a sequence of fields.

## Land preparation

Rice seedbeds are prepared dry, using different size tractors with varying horsepower. The amount of cultivation depends on soil type and condition, and the rice sowing method. For drill seeded rice to achieve uniform depth of seeding, fine seedbeds are required. Such fine seedbeds are more difficult to achieve on clay soils. Coarse, cloddy seedbeds are preferred for water-seeded rice: the clods serve as barriers to seedling drift from wind and wave action.

Frequently, the field is opened with a chisel plow or disc harrow to allow the soil to dry. One or two diskings to reduce clod size may follow. Even though most of the riceland in Australia and the United States has already been leveled, smoothing with laser planes or triplanes is necessary each year to remove high and low surfaces created by equipment operations. High, unflooded areas are ideal for rapid weed growth; low areas collect water and reduce seedling survival. In recent years, large "V" rollers are increasingly being used to provide a smooth but corrugated surface for anchoring water-seeded rice. The roller makes grooves in the soil perpendicular to the prevailing wind direction. When rice seed is broadcast into the water, it lodges at the bottom of the grooves and is protected from uprooting by wind. Rollers can be modified for several field operations, including application of nitrogen, phosphorus, potassium, zinc, and insecticides.

## Varieties

Japonica cultivars are commonly grown in the more extreme latitudes; indicas predominate in the moderate latitudes of the temperate zone. Plant breeding programs have led to locally adapted cultivars (Table 2). Where environments are relatively similar, the same cultivars have been adopted across regions and countries. For example, semidwarf derivatives of Calrose, developed in California, are grown in New South Wales, Australia (Wright et al 1989). Long-grain varieties developed in the United States are grown in Italy and other areas of Europe.

**Table 2. Popular rice varieties in temperate Australia, Italy, and the United States.**

Grain type	Varieties			
	Australia <sup>a</sup>	Italy <sup>b</sup>	USA-South <sup>c</sup>	USA-CA <sup>c</sup>
Short (japonica)		Balilla		S-101 S-201
Medium (japonica)	M7	Lido	Mars	M-102
	Amaroo	Arburie	Mercury	M-201
	Bogoia	Europa	Saturn	M-202
	Calrose			M-401
Long (indica)	Pelde		Lemont	L-202
			Newbonnet	
			Tabonnet	
			Gulfmont	

<sup>a</sup>Wright et al (1989). <sup>b</sup>Bold et al (1988). <sup>c</sup>Rice journal (1988).

All varieties may be used in dry seeding or water seeding. In general, however, the short- and medium-grain cultivars are more tolerant of continuous flooding, showing better vigor in water-seeded conditions than long-grain cultivars.

## Direct seeding methods

The direct seeding methods used in the mechanized rice culture common to the temperate zone can be classified into water seeding and dry seeding.

### Water seeding

Broadcasting pregerminated or dry rice seed into standing water is the most common wet seeding method in the temperate zone. In contrast to the practice in the tropics, dry or pregerminated rice seed is normally not seeded onto puddled soils. Water seeding is practiced on 98% of Italian, 81% of Australian, and 33% of United States rice hectare (Table 3) (Balsari et al 1989, Wright et al 1989). Within the United States, California rice is almost exclusively water seeded (Table 4) (Rutger and Brandon 1981). Water seeding is done mostly by aircraft. In Italy, however, where fields are smaller, water seeding is accomplished with ground-driven broadcast seeders (Balsari et al 1989). Water seeding is rarely done by hand.

**Table 3. Distribution of direct seeding methods.**

Country	Hectareage (%)		
	Water seeded	Drill seeded	
		Prepared seedbed	No tillage
Australia	81	6	13
Italy	98	-	-
United States	33	67	-

**Table 4. Hectares direct seeded and water seeded.**

State	Total hectares ( $\times 10^3$ )	Water seeded (%)	Drill seeded (%)
Arkansas	460	4	96
Mississippi	98	10	90
Louisiana	207	60	40
Texas	133	40	60
California	164	99+	<1

Seedbeds are prepared rough or, if smooth, the soil is corrugated or grooved. Cloddy or corrugated seedbeds provide sites to anchor the seedlings and protect them from wind and wave action. Smooth or slicked-over seedbeds can incur severe stand losses under windy conditions. However, seed burial can be a problem with rough seedbeds—rice seedlings may not emerge through both soil and water.

For water seeding, rice seed is soaked in water 24-36 h and drained another 24 h. Soaking initiates germination and increases seed weight by approximately 30%. The added weight from imbibition allows the seed to sink to the soil surface. Dry seeds may also be water seeded, but the seed must be coated, usually with an inert mixture of talc and a sticker, to increase seed weight. This is because dry seed floats and may drift on the water surface, resulting in uneven stands. In California, 10-15% of the rice hectareage is planted with coated seed sown into standing water.

The most important advantage of presoaking is that germination and seedling emergence occur more rapidly with wet seed than with dry seed. However, presoaking starts the germination process and commits the seed to planting before seed viability is lost. Because dry seed can be planted any time, sowing can be delayed if planting conditions are unfavorable (wind, rain, etc.).

For water seeding, seeding rates of 120-140 kg/ha (dry weight basis) are common. Depending on the seed size of the cultivar, that is approximately 550 seeds/m<sup>2</sup>. Research and experience indicate that 150-250 seedlings/m<sup>2</sup> will provide optimum yields (Table 5). Most commercial varieties can compensate for low seeding rates or

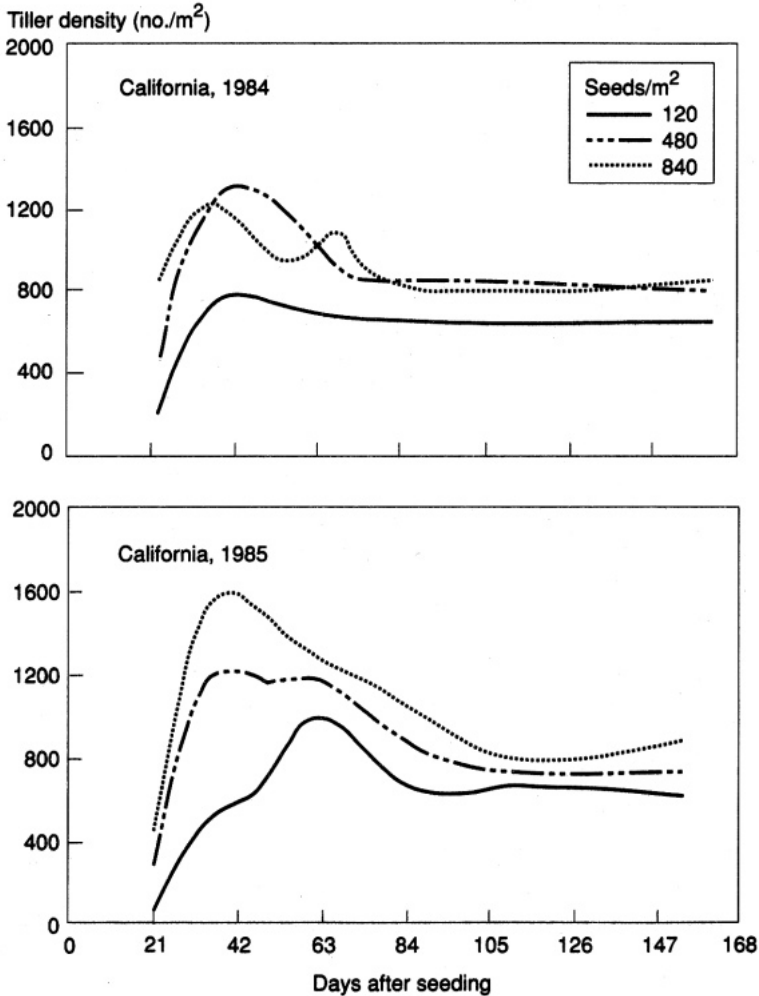
**Table 5. Main effects of stand establishment, yield, and yield components.<sup>a</sup>**

Seeding rate (seeds/m <sup>2</sup> )	Established plant stand (no./m <sup>2</sup> )	Yield (t/ha)	Yield components			
			Panicle density (m <sup>2</sup> )	Grain weight (mg)	Spikelets/panicle (no.)	Filled spikelets (%)
120	122	9.8	571	25.2	90.8	86.6
240	222	10.4	700	25.6	74.8	85.8
360	291	10.6	655	25.8	71.6	86.2
480	371	10.5	709	25.5	64.3	85.6
600	369	10.6	728	25.9	63.1	86.2
840	458	10.6	807	25.9	58.9	86.8

<sup>a</sup> Miller (1989).

poor stand establishment through increased tillering. For example, at seeding rates of 120-840 seeds/m<sup>2</sup>, plant stands varied from 120 to 460 plants/m<sup>2</sup>; final panicle density varied much less, from 570 to 810/m<sup>2</sup> (Fig. 2). At midseason, maximum tillering averaged 800-900 tillers/m<sup>2</sup> at a 120 seeds/m<sup>2</sup> seeding rate; it varied from 1,200 to 1,500 tillers/m<sup>2</sup> at seeding rates greater than 240/m<sup>2</sup>(Miller et al 1991).

Although panicle density (tiller density) contributes most significantly to high yields, other yield components also may compensate for lower panicle densities. A decision to reseed following loss of stand is usually made only if the counts drop below 50-60 seedlings/m<sup>2</sup>. Stands are difficult to establish with reseeding because the oxygen



2. Tiller development across time, averaged across cultivars (Miller et al 1991).

concentrations in the soil and water are very low by the time a reseeding decision is made.

High seeding rates may result in stands that are too dense. Overly dense stands may increase disease severity, lodging, and incidence of other factors that reduce yield.

### **Dry seeding**

Rice seed is drilled or broadcast and incorporated into dry soil. Several variations of drill seeding are used, depending on cropping history and tillage practices. Drilling into well-tilled seedbeds is most common in the southern United States and on 6% of the ricelands of New South Wales, Australia. Drilling into nontilled stubble or pasture is practiced on 13% of the ricelands of New South Wales and approximately 1 % of those of California. Aerial or ground broadcasting onto dry soils followed by light incorporation is also used in some areas (University of California 1983, Wright et al 1989). Drill seeding requires less seed, but more time than broadcast seeding. Drill seeding results in more uniform emergence because seeding depth is more uniform than it is with broadcast seeding.

Well-prepared and relatively fine-textured seedbeds are preferred for drill-seeded rice. The seed is drilled 1-4 cm deep at 15-17 cm row spacing. More shallow depths are preferred on rough seedbeds, on soils that crust, and in cool weather, to speed seedling emergence. Germination after planting is promoted by intermittent irrigation, termed flushing, although timely rainfall may provide the first irrigation. Well-leveled soils that drain readily are necessary to avoid puddling. Ricefields are permanently flooded when the crop reaches the three-leaf to early tillering stages.

No-tillage stubble drilling and drilling into the sod of standing pasture are variations of drill seeding. The soil has not been tilled, and the stubble may or may not have been burned before seeding. Pastures usually have been heavily grazed by sheep or treated with nonselective herbicides before planting. The drills used for direct seeding into stubble or pasture are of heavier construction and have triple discs to open the untilled soil for seed placement. Irrigation flushing and permanent flooding are similar to standard drill-seeded rice culture methods.

For conventional drill seeding, seeding rates range from 100 to 140 kg/ha. Higher rates are used for no-tillage and pasture seeding, because uniform seed placement in undisturbed soils is more difficult. For broadcast dry seeding, rates are 170 kg/ha—higher than for drill seeding and about the same as for wet seeding.

### **Water management**

Once the crop is established, the water management strategies used in Australia, Italy, and the United States are similar. Rice is permanently flooded for most of the growing season, although short drainage periods may be needed to correct specific crop disorders. Water use varies with weather, soil type, and management practices. About 1,200 mm of water is needed for evapotranspiration, but the amount of irrigation water delivered may be 2,000 mm or more.

Field leveling is the most important factor in efficient irrigation management. The permanent flood is maintained at 7-12 cm depth during most of the vegetative period. During reproductive growth, large diurnal temperature changes in these temperate climates may cause cold-induced floret sterility. Because water can act as a heat sink to buffer these large fluctuations, irrigation depth is commonly increased to 20-30 cm to protect developing panicles from cold night temperatures.

The field is drained in preparation for harvest. The time of drainage is critical: adequate soil moisture must be available for grain filling, but the soil must be dry enough to support mechanical harvesting equipment by the time the grain is dry enough to harvest.

## Nutrition

Nitrogen is the nutrient most commonly added in rice production. Phosphorus, potassium, and zinc may be applied, depending on soil requirements. The nitrogen requirement varies with soil type, cropping history, cultivar, and planting date. In general, 100-200 kg N/ha in a reduced form (urea, ammonia) is applied before the permanent flood, except following pasture in Australia, where 0 to 150 kg N/ha is applied. In water-seeded rice, N is incorporated 5-10 cm deep into dry soil, to minimize denitrification and ammonia volatilization losses after flooding. In drill-seeded or other dry-seeded rice culture, some nitrogen may be applied at seeding, but one-third to two-thirds is applied immediately, before the permanent flood (usually at the 3-leaf to early tillering stages). Water- or dry-seeded rice is topdressed with 30-50 kg N/ha during panicle initiation, if leaf tissue analysis or other crop indicators suggest nitrogen is needed.

Phosphorus is applied when soil tests or plant symptoms indicate a deficiency. In water-seeded or broadcast dry-seeded rice, 20-30 kg P/ha is incorporated before seeding. In drill-seeded rice, similar amounts may be drilled at planting.

Potassium is applied when soil tests, plant symptoms, or cropping history indicate a deficiency. Potassium is applied more often and at higher levels in Italy than in Australia or the United States. In Italian rice production, 80-150 kg K/ha is commonly used; in other areas, 40-60 kg K/ha is most often used.

Zinc deficiency is common in the high-pH, sodic soils found in some regions of the temperate zone. Soil tests may be used as an indicator of zinc deficiency. Severe deficiencies result in complete stand losses; deficiencies in marginal soils frequently result in symptoms at the seedling stage in cool weather. Preflood or early postflood applications of 8-16 kg Zn/ha effectively correct this deficiency. Zinc is not incorporated but is applied to the soil surface before planting.

## Pest management

A wide range of weeds, diseases, and invertebrate and vertebrate pests infest rice in the temperate regions. Weeds are a major problem, because they have a more competitive

advantage in direct seeded than in transplanted rice. Annual grasses, broadleaves, and sedges commonly infest rice. The most important are the *Echinochloa* complex of barnyardgrass and watergrass. The aquatic sedge *Cyperus difformis* and other *Cyperus* and *Scirpus* species are also problems. *Sagittaria*, *Alisma*, and *Ammannia* spp. are major broadleaf competitors.

While all these weed species may be found in water-seeded or dry seeded rice, the proportion of each species varies with the type of rice culture. Crop culture has an important impact on the relative abundance of competing weed species and on their control. The grass weed species more readily invade dry-planted and flush-irrigated rice than do the aquatic species. The large-seeded watergrasses and aquatic flora are more abundant in water-seeded rice, Cultural practices combined with herbicide treatments are used to minimize the impact of weeds on yield (Department of Agriculture, New South Wales 1984; Smith and Hill 1990; University of California 1983).

Diseases vary widely with region and country. Blast caused by *Pyricularia oryzae* is a major problem in Italy and the more humid subtropical environments of southern United States, but is not found in the arid regions of Australia and California. Stem rot *Sclerotium oryzae* and sheath blight *Rhizoctonia* spp. are problems in other regions. *Pythium* spp. may infect seedlings, particularly when the crop is drill seeded on clay soils in cool weather.

Rice water weevil *Lissorhoptrus oryzophilus*, bloodworm *Chironomus tepperi*, stinkbug *Oebalus pugnax*, armyworm *Pseudaletia unipuncta*, leaf miner *Hydrellia* spp., and other invertebrate pests infest mechanized rice in the temperate zone. Additional vertebrate pests include snails *Physastra* spp., tadpole shrimp *Triops longicaudatus*, swamp crayfish *Procambarus clarki*, and others. Method of sowing may alter the habitat for several of the invertebrate pests. For example, the rice water weevil and tadpole shrimp are not major problems of dry seeded rice, but may heavily infest water-seeded rice. Vertebrate pests include rats, small birds, and water birds (principally ducks).

## Harvesting

In Australia, Italy, and the United States, rice is harvested with self-propelled combines. To avoid grain fissuring in the field and mechanical damage in the combine, the crop is harvested at 18-23% grain moisture. Short- and medium-grain japonica cultivars are harvested at 22-23% moisture (Department of Agriculture, New South Wales 1984); long-grain indica cultivars at 18-21% moisture. The grain is delivered to on-farm and centrally located dryers, where it is carefully dried to maintain milling quality. Much of the rice of Australia, Italy, and the United States enters the international market as high-quality table rice.

Rice yields in Australia, Italy, and the United States are among the highest in the world, ranging from 5.8 t/ha in Italy to 8 t/ha in Australia in 1989 (Clampett 1989) (Table 6). Yields in the United States range from 5 t/ha in the subtropical

**Table 6. Hectarage, yield, and production of rice in Australia, Italy, and the United States in 1989.**

	Hectares ( $\times 10^3$ )	Yield (t/ha)	Total production (t)
Australia			
New South Wales	100	8.0	800
Italy			
Milan	199	5.8	1150
United States			
Arkansas	460	6.3	2871
California	164	8.8	1458
Florida	6	5.6	35
Louisiana	207	5.0	907
Mississippi	98	6.4	603
Missouri	32	5.8	184
Texas	133	6.4	869

environment of Louisiana to 8.8 t/ha in the long-day, rain-free environment of California.

## Future issues for direct seeded rice

### Stand establishment

Planting costs are substantially less for direct seeding than for transplanting. However, the germinating seed and emerging seedlings are vulnerable to oxygen deprivation, seedling diseases, and a host of other abiotic and biotic disorders. Improvements in seedling vigor and rapid early growth, tolerance for submergence and low oxygen environments, cold tolerance in the temperate zone, and other factors would greatly improve direct seeding methods in the temperate and tropical regions, and facilitate their adoption.

### Weed control

Where rice is dry seeded and intermittently irrigated, weeds germinate and emerge simultaneously with rice and competition begins early in the crop's development. In water-seeded rice, weeds may germinate when the field is flooded, 3-7 d before planting. Improvements in rice seedling vigor, rapid emergence, tolerance for 20 cm or deeper water in water-seeded rice, canopy architecture (horizontal leaf display early and vigorous root development), selective herbicides, allelopathy, herbicide tolerance, and adaptation of rotational crops to wet soils could make rice more competitive with weeds and break weed cycles.

### Environmental quality

In the mechanized direct seeded rice crops of the temperate zone, water and air quality are major issues that impact the rice farmer. These issues are not specifically related to direct seeded rice; their solutions are important to all of the world's rice ecosystems.

Herbicides are widely used to control the weeds that are a major constraint to high yields in direct seeded rice. The movement of herbicides and, to some extent, other pesticides into potable surface waters has been noted in California and other regions of the United States and in Italy. Improvements in irrigation systems, biological methods of pest control, cultivar improvement for pest resistance, and more selective and environmentally benign pesticides would greatly reduce problems with environmental pollution and contamination of downstream water from ricefields.

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## Notes

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*Citation information:* International Rice Research Institute (1991) *Direct seeded flooded rice in the tropics*. P.O. Box 933, Manila, Philippines.

# Germination and crop establishment of direct seeded rice in the south of France

J. M. Barbier, J. C. Mouret, and N. Stutterheim

In the south of France (Rhône River Delta, 42° north latitude), rice cultivation covers nearly 20,000 ha. Farmers use direct seeding and permanent flooding. Dry, nontreated seeds are broadcast into the floodwater. Because of ecological (saline soils) and climatological (cold temperature, strong winds) constraints, germination is hampered and young plants can be easily uprooted. Farmers use 180-230 kg seed/ha, but only 10.50% survive, depending on the situation, and stands are thin and not homogeneous.

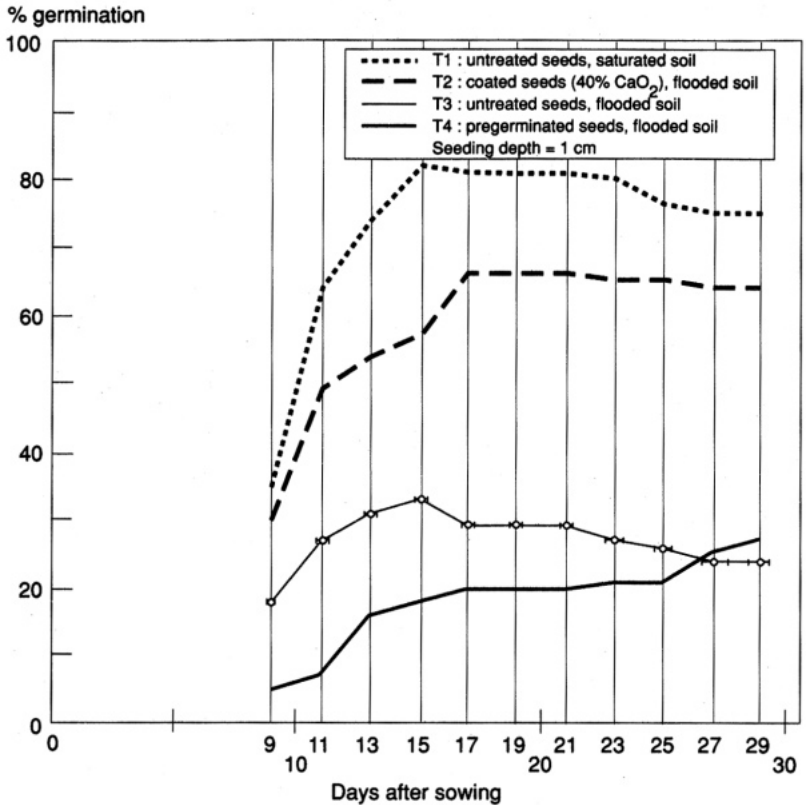
Our first objective was to improve crop establishment, to save seed and to obtain homogeneous and vigorous stands. Our initial research used a global approach and popular varieties to identify decisive variables and to quantify their interrelationships.

Depending on the stability of the seedbed structure (a function of soil texture, salinity, and organic matter content), the initial status of the soil created by land preparation is modified after flooding. The degree of change in the soil surface structure is a function of wind and water control; that determines the degree of seed covering by soil. Oxygen availability for germination is related to the depth of covering and also to available organic matter (crop residues) and water management practices.

The next step was to search for improvement in crop establishment, using current cultivation practices and exploring new methods of planting. We developed guidelines for optimal seedbed preparation (to avoid both extreme seed covering and plant uprooting) and for water and crop residue management. These recommendations have already led to better control of crop establishment, but further improvements are needed.

For that purpose, we compared different seed treatments and water management techniques: calcium peroxide coating, pregermination, and gibberellic acid treatment with broadcast or drilled seeds, in flooded or saturated soil. Our results show that pregermination improves only plant vigor (see figure). Calcium peroxide coating in addition shows much less seed loss. Germination in nonflooded seedbeds gave the best results, but this technique requires important changes in water management.

The consequences of these changes on crop growth (by action on weeds, nitrogen, and salt dynamics) are being studied.



Effects on germination of different seed treatments and water management practices.

## Notes

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Problems with continuous seeding of rice in Malaysia

M. A. Supaad and A. W. Cheong

Rice cultivation has come a long way and has gone full circle. At the dawn of cultivation, rice seeds were manually sown or dibbled. Transplanting evolved. At first, it was manually done; very recently, it has been mechanized. The evolution was an attempt to regulate plant density and homogenize crop growth, with the expectation of stabilizing yield. Now the cycle is turning back to direct seeding, purposefully chosen where technology is available, or adopted out of necessity for want of labor (direct seeding takes as much as 25 fewer labor days/ha than transplanting).

The extent of direct seeding in Malaysia has increased within the last decade, from negligible coverage to more than 50% of all rice crops. Some irrigation schemes are now fully into direct seeding. What is disheartening is when direct seeding is hastily adopted for its apparent ease of operation, at least during crop establishment, without realizing that subsequent crop management may not be as easy nor as effective. Problems in direct seeding aggregate right through to harvest.

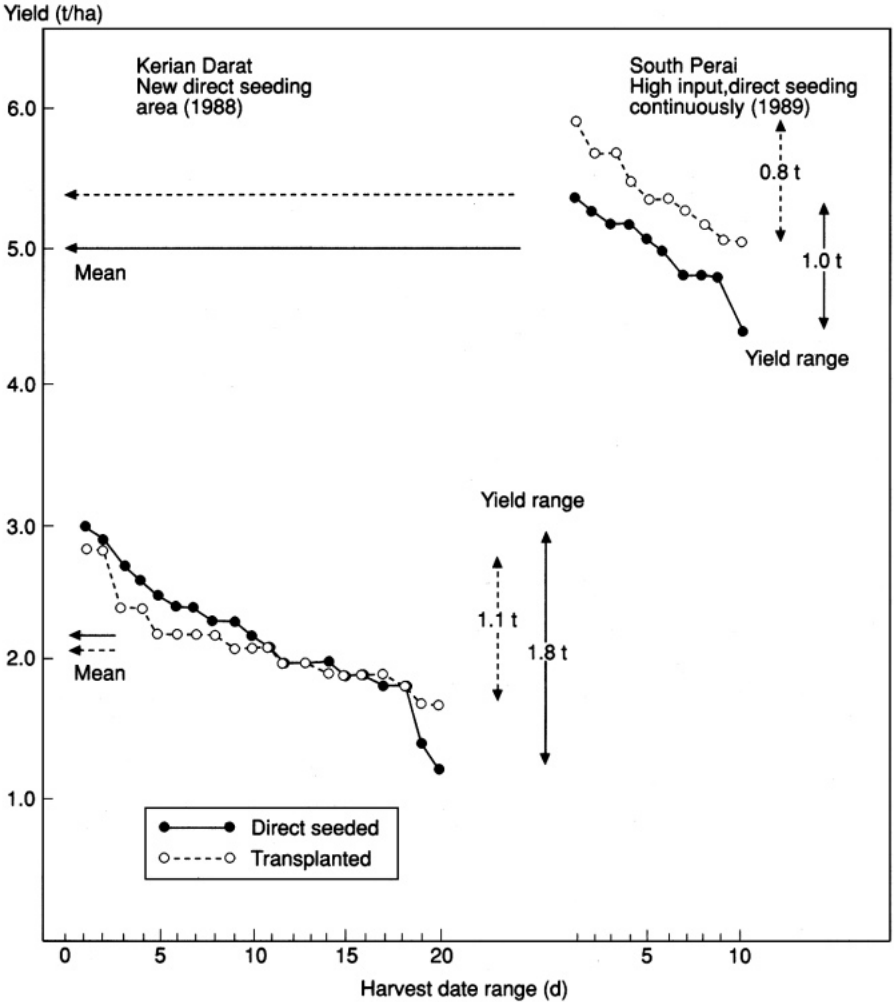
Among the problems encountered, water irregularity and weed buildup cannot be easily overcome. Most pertinent is the change in weed species, from broadleaves and sedges to grasses. The infestation of grasses is escalating, often with more than one dominant species (e.g., *Echinochloa crus-galli* and *Leptochloa chinensis*, followed closely by *Ischaemum rugosum*). These weeds are seldom easy to deal with, particularly in areas where direct seeding is entrenched but not well endowed with the necessary inputs.

In new direct seeded areas, haste in committing fully to the system without first acquiring the appropriate technology has affected crop yield most. Yield losses in unweeded direct seeded crops are much higher than in unweeded transplanted crops. Losses in excess of 1 t/ha are not uncommon, and some crops have been completely lost to weeds.

Under such circumstances, reverting to transplanting could be the only option. But the labor previously available for transplanting may not be there any more. This is when mechanized transplanting has to be considered in earnest (excessively staggered cropping would arise if transplanting were to be done with limited labor).

More labor and species-specific herbicides are needed to manage weeds effectively in direct seeding. A well-planned land preparation program, including tillage and land leveling, integrated with selective herbicides, should provide a good start to a direct seeded crop—if water is readily available when needed (which is often not possible, especially in dry seeding).

In one long-term irrigation scheme, where progressive and innovative farming methods are practiced, yields from direct seeded rice crops sown in the wet season have been sustained at a very respectable level (see figure). Some crops



Yield potential of direct seeded and transplanted rice (MR84) with different input levels in two different areas of Malaysia.

average more than 6 t/ha, with high inputs and vigilant crop management. A new scheme that has been open less than 10 yr after clearing of swamps uses similar high inputs. But direct seeded yields have not been consistently as high, even though an odd crop has been reported to have yielded in excess of 8 t/ha. Obviously, high level inputs must be commensurate with equally high management competence.

Direct seeded yields in the dry season, irrespective of varietal maturation (from as early as 100 d to later than 130 d), have not been as high as in the wet season, or as high as yields of transplanted rice in the wet or dry season, using the same range of varieties (110-140 d duration). Although crop duration is shorter with direct seeding, crop exposure in the main field is longer than for a transplanted crop, with a commensurate higher probability of pest and disease buildup.

Farmers, in fear of not getting a well-established crop stand, often sow at very high seed rates (exceeding 100 kg/ha). Under normal circumstances, where land preparation has been thorough and water use efficient, a seed rate of 60 kg/ha would be more than sufficient. The result is a very dense and compact crop. Besides imposing a higher demand for inputs like fertilizer, such a crowded, luxuriant crop attracts more pests and diseases, which, in turn, calls for more crop care if yield losses were to be avoided. Such an end does not justify a very high seed rate, even to ensure against poor crop establishment.

The influence of selected varietal traits cannot totally prevent lodging in a direct seeded crop. When conditions are unfavorable, a direct seeded crop has been seen to have completely lodged, when a transplanted crop in the immediate vicinity may still be more than half standing. High inputs, not judiciously used, can worsen such damage.

Because of the inherently staggered establishment of a direct seeded population, overlapping crop stages can be pronounced. As such, appropriate use of inputs cannot be determined as easily as in a transplanted crop. Managing a direct seeded crop is not easy. With continuous direct seeding, crop yields fluctuate, resulting in a total yield lower than that with continuous transplanting (see figure). Quality also is affected by contamination with weeds, volunteer plants, and wild rice.

A truly integrated management system could perhaps check long-term declines in quality and quantity of yield with continuous direct seeding. Technology for crop management needs to be consolidated, to maintain yields at reasonable costs.

## Notes

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# Field leveling and direct seeding methods for rice in Portugal

D. Luzes

In Portugal, irrigated rice is grown on 34,000 ha, with the 140,000 t annual production supplying approximately 2/3 of national consumption. The rice crop is grown exclusively by direct seeding under flooded conditions.

Land leveling and seeding are two important operations in this system. Three treatments resulting from the combination of two leveling methods and two seeding methods were tested in the Sado valley in 1988 and 1989 dry seasons: broadcast seeding by airplane onto a flooded field that had been conventionally leveled, and drill seeding and broadcast seeding onto dry fields leveled by airplane using laser equipment. (Conventional leveling is done with a tractor mounted with an iron blade after the field has been flooded. The water level serves as an orientation to the operator's work.) Grain yield, dry matter production, relative growth rate, leaf area index, and plant population were compared.

Yields with drill seeding and broadcast seeding onto dry fields were similar; yields with conventional leveling were 30% lower. Plant population seemed to account for the yield differences. Poor germination and emergence had a strong influence on development of the productive population. The main factors responsible for the population reduction were difficult oxygen diffusion caused by a high water level (20 cm), strong wind velocities (4.5 m/s at 1800 h), and a decrease in available light intensity due to water turbidity with conventional leveling (see table). Dry matter production per plant and relative growth rate were similar in all three treatments.

Leaf area index was closely correlated with yield in a parabolic relationship. The data indicate that, at near optimal growing conditions, an asymptotic yield response to population density occurs.

## Notes

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**Rice plant (Ringo variety) population densities at different growth stages, field emergence, and grain yield as affected by land leveling and seeding method in the Sado Valley (lat = 38° 23, long = 8° 31, alt = 51 m), Portugal.**

Treatment	Seeding (seeds/m <sup>2</sup> )	Plant population (no./m <sup>2</sup> )	Emergence (%)	Panicles (no./m <sup>2</sup> )	Yield at 120/0 moisture (t/ha)
Conventional method of leveling + broadcast seeding onto flooded fields	567	157	28	241	4.8
Land leveling by plane and laser equipment + drill seeding onto dry fields	542	290**	54	304*	6.7**
Land leveling by plane and laser equipment + broadcast seeding onto dry fields	635	279**	44	378**	6.8**
LSD 5%	-	38.0		55.8	0.63
LSD 1%	-	54.0		80.3	0.91

# Direct seeding methods for rice in Venezuela

J. J. Castillo and O. Paez

A wide range of methods are used for direct seeding rice in Venezuela: dry land, fresh mud bed, and inundated soil. Although 85% of the seed used is pregerminated, dry seed may be used in dry land and occasionally in fresh mud bed sowing. Dry land seeding is common among upland and rainy season rice growers. Fresh mud bed is more common on small farms (less than 20 ha), but is also used on some larger farms (more than 100 ha). Inundated soil requires well-leveled land, which is more commonly achieved by larger scale farmers.

Direct seeding is done with tractors (5%), with airplanes (75%), or by hand broadcasting (20% of farms larger than 50 ha and 100% of those less than 20 ha). Increasing costs of fuel and airplane maintenance have pushed air seeding costs to three times more than hand seeding (4 labor d/ha). Lack of labor and pressure for more rapid sowing restrict greater use of hand seeding. Seeding rates of 130 to 150 kg/ha are common, but with airplane or tractor seeding, rates can be as low as 100 kg/ha. No yield differences have been reported using either method. Best distribution of seed is by plane or tractor.

## Notes

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# Fertilizer management in broadcast-seeded rice in Egypt

A. Tantawi Badawi, F. N. Mahrous, and M. S. Balal

Rice occupies about 0.45 million ha in Egypt, with a national average yield in 1989 of 6.5 t/ha. Direct seeded rice has been increasing, and covered more than 20% of the total area in 1989. Field experiments at the Agricultural Research Station, Kafr El-Sheikh, 1987 and 1988 seasons, were designed to study the effect of nitrogen level, timing, and application method on broadcast-seeded rice. Grain yield, biomass, harvest index, yield components, N uptake at 95 d after sowing (panicle initiation), and total N uptake at harvest (straw + grain) were measured. The rice experiments were preceded by barley both seasons. A split-split-plot design with four replications was used, with three rice varieties (Giza 181, Giza 175, and Giza 171) in the main plots, N level in the subplots, and time and method of N application in the sub-subplots. Analysis was on combined data.

N recovery was calculated by Rao's formula:

$$\text{N recovery (\%)} = \frac{\text{N uptake by fertilized crop} - \text{N uptake by unfertilized crop}}{\text{Amount of N applied}} \times 100$$

Yield and contributing variables are shown in the table. Giza 171 had the lowest yield, Giza 175 the highest number of panicles/m<sup>2</sup>.

Nitrogen level significantly affected yield. Varieties differed in their response. Yield for Giza 181 and Giza 171 increased with up to 150 kg N/ha. Increases in panicles/m<sup>2</sup>, panicle weight, and grains per panicle with each increment of N caused the significant effect on yield.

Methods of nitrogen application also significantly influenced yield. Split application markedly increased yield, with the highest yield from the triple split. Split application resulted in more panicles, heavier panicles, and more grains per panicle.

Giza 181 had the highest N uptake at panicle initiation as well as the highest total N uptake at harvest. N uptake increased gradually with N rate up to 150 kg N/ha. The superiority of the triple split application might be attributed to N availability at different rice growth stages as well as to decreased N loss to ammonia volatilization and nitrification and denitrification with broadcast-seeded rice.

**Grain yield, yield components, and nitrogen uptake by some direct seeded rice varieties, under different levels, time, and method of N application.**

Treatment <sup>a</sup>	Grain yield (t/ha)	Panicles (no.)	Panicle weight (g)	Grains/panicle (no.)	Unfilled grains (%)	1,000 grain weight (g)	N uptake at PI (kg/ha)	Total <sup>b</sup> N uptake (kg/ha)
<b>Variety</b>								
Giza 181	8.9	428	2.04	80.4	10.2	25.65	112.0	145.8
Giza 175	8.8	463	1.83	89.9	12.2	20.55	95.4	128.2
Giza 171	7.6	330	2.33	100.1	9.9	24.44	77.1	116.6
LSD 0.05	0.17	19	0.23	5.4	0.4	0.41	21.6	5.7
LSD 0.01	0.26		0.36	7.8	0.9	0.67	36.6	8.6
<b>Nitrogen level</b>								
Control (no N)	6.8	353	1.73	77.4	8.9	23.94	61.4	82.0
50 kg/ha	8.3	419	2.03	91.3	9.6	23.79	98.1	129.3
100 kg/ha	9.0	425	2.18	97.6	10.6	23.57	114.6	144.8
150 kg/ha	9.6	460	2.28	98.1	11.9	23.64	137.7	166.6
LSD 0.05	0.2	29	0.17	5.7	0.5	0.26	24.6	15.6
LSD 0.01	0.2	35	0.23	7.6	0.9	0.35	39.0	20.3
<b>Application method</b>								
Incorporation (inc)	8.1	404	1.92	87.0	9.9	23.79	85.2	116.4
1/3 inc + 2/3 at MTS <sup>b</sup>	8.4	428	2.03	92.0	12.2	23.55	98.0	125.3
2/3 inc+ 1/3 at MTS	8.3	405	2.01	91.6	10.9	23.64	100.1	128.1
1/3 inc + 1/3 at MTS + 1/3 at PI	8.9	430	2.16	94.8	9.4	23.52	129.0	153.2
LSD 0.05	0.2	21	0.14	4.8	0.5	0.24	10.6	10.2
LSD 0.01	0.2	31	0.18	7.8	1.0	-	15.3	14.6

<sup>a</sup> MTS = maximum tillering stage, PI = panicle initiation. <sup>b</sup> Total N uptake from grain and straw at harvest.

N recovery in the grain and straw increased up to 50 kg N/ha, then started to decrease with increasing N. The efficiency of grain response/kg N (agronomic efficiency) was similar to N recovery. The N response curve indicated that maximum yield (9.5 t/ha) when the preceding crop was barley was obtained at around 150 kg N/ha.

## Notes

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*Citation information:* International Rice Research Institute (1991) Direct seeded flooded rice in the tropics. P.O. Box 933, Manila, Philippines.

# Using GA<sub>3</sub> seed treatment in direct seeded rice in southern U.S.A.

R. S. Helms, R. H. Dilday, and R. D. Carlson

Modern Semidwarf rice *Oryza sativa* L. cultivars—80-120cm in height at maturity, with short and more upright leaves, greater N responsiveness without lodging, and higher grain yields than taller traditional rice cultivars (Turner et al 1982)—are becoming more popular with rice producers in the United States. Semidwarf rice cultivars were seeded on 790,365 ha in the southern rice-growing area in 1988 (Matlick 1988).

Stansel (1984) warned that there may be problems with seedling emergence of direct seeded semidwarf rice cultivars, and that changes in management practices may be required to maximize their economic productivity. Rice seedling emergence is a function of mesocotyl and coleoptile elongation. The mesocotyl is the internode between the coleoptile node and the point of union of the root and the culm. The coleoptile is the cylinder-like protective covering that encloses the young plumule (De Datta 1981). Turner et al (1982) reported that poor stand establishment of semidwarf cultivars is largely attributable to short mesocotyl length, and noted that the semidwarfs have shorter mesocotyls than traditional, nonsemidwarf rice cultivars.

We evaluated gibberellic acid (GA<sub>3</sub>) seed treatments for mesocotyl and coleoptile elongation in rice, and compared stand establishment, plant height, and grain yield.

Lemont rice, a semidwarf cultivar, was treated with GA<sub>3</sub> at 10, 50, and 100 mg ai/kg seed. The slantboard technique described by Jones and Peterson (1976) was used in a growth chamber study to determine the potential length of the mesocotyl and coleoptile of seedlings grown in darkness.

In 1988 field studies at the Southeast Branch Experiment Station, Rohwer, Arkansas, Lemont was seeded at 112 kg/ha in Desha silt loam (Vertic Haplaudolls). Plots were 9 drill rows wide (15-cm spacing) and 4.6 m long. Stand counts were taken in two 0.09-m<sup>2</sup> areas before flooding. Plant height at maturity was measured from the soil level to the top of the extended panicles at two locations in each plot. The plots were combine-harvested and grain yields adjusted to 12% moisture.

In the growth chamber study, GA<sub>3</sub> seed treatments significantly increased mesocotyl and coleoptile elongation and total length (see table). In the field

### Effect of GA<sub>3</sub> seed treatment on direct seed rice.

GA <sub>3</sub> (mg/kg)	Growth chamber study			Field study			
	Mesocotyl (mm)	Coleoptile (mm)	Total (mm)	Stand density (plants/m <sup>2</sup> )	Plant height (cm)		Yield (t/ha)
					20 DAS <sup>a</sup>	Maturity	
-	1.7	9.4	11.1	127	8.0	93.8	7.7
10	16.3	26.7	43.0	191	11.1	92.8	8.2
50	12.4	24.8	37.2	191	15.7	91.3	8.0
100	15.8	22.6	38.4	201	16.2	92.1	8.3
LSD	3.6	5.9	7.7	53	3.0	ns	ns

<sup>a</sup> DAS = days after seeding.

study, GA<sub>3</sub> significantly increased stand density and plant height 20 d after seeding. There was no significant difference among seed treatments in plant height at maturity or grain yield.

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# Research priorities for direct seeded rice in the tropics

Two groups discussed management problems in moving from transplanting to direct seeding in irrigated and favorable rainfed lowland rice and one group discussed the ideotype concept for breeding high-yielding rice for direct seeding. A matrix was used to target problems, opportunities, and research priorities, with plant characteristics and crop management on one dimension and agroecological zone, inputs, and direct seeding methods on the other (see table).

Participants agreed on the need to establish a universally accessible data base which should include the following information: Where and how direct seeding is practiced, and where the practice is increasing; yield loss or benefit of direct seeding; time and cost benefit of direct seeding (particularly in low-input tropical systems with unreliable technology and low opportunity cost of labor).

Economic and social questions also are important. It was suggested, for example, that direct seeding may be least applicable in low-input tropical systems because of its technical unreliability and the low opportunity cost of labor used in transplanting.

Features of an ultrahigh-yielding rice plant might be grouped into lodging resistance, growth behavior, tillering pattern, nutrient dynamics, and root dynamics.

*Lodging resistance.* Short to intermediate height is desirable. Good seedling and plant anchorage through early root growth and deep-rootedness are desirable. Greater stem thickness should be incorporated into the ideotype.

*Growth behavior.* Time sequences of leaf area development and dry weight partitioning need definition. Quick early growth (before panicle initiation) is desirable. Could hybrid vigor be a source of seedling vigor? Erect leaves are thought to be desirable for high-input systems. Growth duration is not a problem: "same as transplanted rice minus 10 days" was suggested. The N gradient from old to young leaves may also be of physiological interest in breaking yield barriers.

*Tillering pattern.* Tiller population per hectare is the important variable. Research is needed on tiller dynamics, not simply on tiller number and panicles initiated. It is desirable to prevent tillering after panicle initiation, and to control number of tillers by seed rate (genotype), not fertilizer. Physiologists identified the need for a range of genotypes and isolines with 2-6 and many tillers, to carry out comparative experiments to more closely define a high-yielding ideotype.

**Problems on research areas and systems identified for dry seeded rice (DSR) and wet seeded rice (WSR).**

Characteristics or management operation	Temperate climate				Temperate climate	
	Low input		High input		DSR	WSR
	DSR	WSR	DSR	WSR		
Land preparation						
When to plow	*					
How to control seed depth	*	*				
Germination timeliness	*	*				
Control of pests	*	*	*	*	*	*
Fast emergence and elongation					*	*
Cold tolerance						
Submergence (tolerance for aerobic, then reduced condition)	*	*	*	*	*	*
Tillering <sup>a</sup>	*	*	*	*	*	*
Nutrition <sup>b</sup>	*	*	*	*	*	*
N or water control			*	*		
Weed control <sup>c</sup>						
By crop	*	*				
By herbicides <sup>d</sup>	*	*	*	*	*	*
Insects and diseases <sup>a</sup>	*	*				

\*=important. <sup>a</sup>Question as to whether it is necessarily desirable to move to low tillering as system becomes more sophisticated. <sup>b</sup>Specific need to research or consider the efficiency of N fertilizer in all direct seeding systems, particularly in relation to water management at the seedling stage of dry seeded, low-input tropical rice. Consider role and efficiency of legume crops before rice for efficient N release after soil becomes flooded. <sup>c</sup>Weed control is more critical in direct seeded than in transplanted rice, in all systems. Early canopy closure is desirable to combat weeds, but it may predispose the rice crop to disease and result in excessive leaf growth and low harvest index. <sup>d</sup>Increased environmental concern with pressures on traditional herbicides requires research on less environmentally damaging control agents (e.g., fungi, allelopathy). <sup>e</sup>There is particular concern over control of pests in dry seeded, low-input crops; seed and harvesting pests; seedling damage by ducks, etc.

*Nutrient dynamics.* There is a need to research nitrogen use efficiency in terms of uptake, utilization, and redistribution. The latter is tied to research on the value of the stem as a sink or source for both N and carbohydrate; the cost of leaf senescence during grain filling, in terms of how much N and C reach the grain; and the desirable architecture of the panicle. Preliminary discussion indicated the aim should be synchronous seed filling (uniform and high-density grains, such as might arise from primary branches of the panicle) to overcome the problem of seed quality.

*Root dynamics.* Under wet seeding, a direct seeded plant requires anchorage in a structureless medium—good early root growth, geotropism. Evidence that the roots of direct seeded rice reach peak mass, then decline earlier than roots of transplanted rice is a concern in nutrient uptake and tolerance for wind. Patterns of root growth and their

